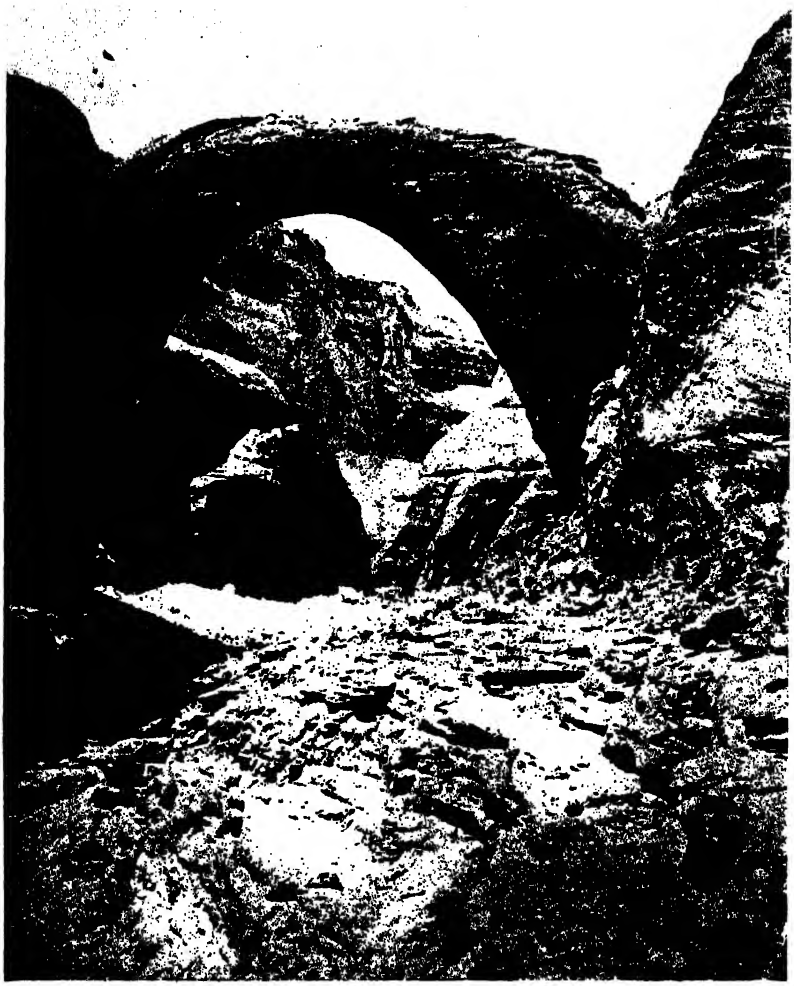

Frontispiece

Barohoini Natural Bridge (Piute for rainbow); northwest of Navajo Mountain, southern Utah. Work of erosion in LaPlata Sandstone. Height 398 feet; width between abutments 278 feet; causeway at top 33 feet wide.

(Photo by H. E. Gregory.)

A TEXT-BOOK OF

GEOLOGY

FOR USE IN UNIVERSITIES, COLLEGES, SCHOOLS OF SCIENCE, ETC., AND FOR THE GENERAL READER

PART I—PHYSICAL GEOLOGY

BY

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PART II—HISTORICAL GEOLOGY

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PART I

SECOND, REVISED EDITION

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PREFACE TO PART I, SECOND EDITION

PREFACE TO THE SECOND EDITION

A new edition of a textbook, especially in a scientific subject like Geology, in which fresh material is constantly appearing, demands no particular explanation. The plan and scope of the work remains unchanged, and in the revision and the addition of new matter in many places the effort has been made to keep the length of the work essentially the same.

The author is indebted to various friends and correspondents for corrections, helpful criticisms, and suggestions for betterments, to whom he desires to extend his thanks and appreciation for the interest they have shown and the pains they have taken in the matter. He would like to mention in this connection Mr. C. K. Needham, Dr. H. H. Robinson, who redrew several figures, and especially Prof. Douglas W. Johnson of Columbia University for many valued suggestions.

In like manner his thanks are due also to his colleagues, Professor H. E. Gregory, Professor A. M. Bateman and the late Professor Joseph Barrell.

Owing to illness, the revision of the proof has been kindly undertaken by Professor Schuchert and Miss Clara Mae Le Vene.

L. V. PIRSSON.

SHEFFIELD SCIENTIFIC SCHOOL OF YALE UNIVERSITY,
NEW HAVEN, CONN.,
May, 1919.

FROM THE PREFACE TO THE FIRST EDITION

For many years the author of this book has been called upon to give the first course in Physical Geology to large classes of students, among whom are to be found those pursuing courses leading to professional work in various branches of Engineering, Mining, Metallurgy, Forestry, Chemistry, etc., and in Geology itself, to whom therefore the subject has a direct technical value or serves as a basis for further technical studies. Naturally these students find a first general course in Physical Geology one of cultural interest as well.

In the pursuit of this work the writer has long felt the need of a

textbook which, while presenting the broad facts and principles of the science from the latest viewpoint, should have a character somewhat different, and a balance more even in the subject matter composing it, than is to be found in available texts.

Although original matter or views of problems have been incorporated in places, it is obvious that the preparation of a work of this nature must mainly be one of selection of the subject matter from published material. It would be impossible to give the greatly varied sources from which it has been drawn, but it may be mentioned that the general treatises of Dana, Geikie, Chamberlin and Salisbury, Haug, Suess, and others, together with the wealth of material embodied in the reports and bulletins of the United States Geological Survey, have been freely used, as well as other works in special fields too numerous to mention.

For efficient help, freely given, in the reading and preparation of different parts of the text, the author wishes to render grateful acknowledgment to his friends and colleagues, Professors J. P. Iddings, J. D. Irving, W. E. Ford, and especially to Professor Joseph Barrell, whose criticism and advice were of the greatest service.

In the matter of illustrations the writer desires to express his obligations especially to Dr. George Otis Smith, Director of the United States Geological Survey, who placed at his disposal its great mass of photographic material, the proper credit for these photographs being given in each case; to Mr. J. J. H. Teall, recent Director of the Geological Survey of Great Britain; to Professor G. P. Merrill of Washington, D. C.; to Professor J. E. Talmage of Salt Lake City; to Mr. G. W. Grabham of Khartoum, and to many other friends whose names are credited in each case.

L. V. PIRSSON.

SHEFFIELD SCIENTIFIC SCHOOL OF YALE UNIVERSITY,
NEW HAVEN, CONN.,
Dec., 1914.

TABLE OF CONTENTS

PART I. — PHYSICAL GEOLOGY

DIVISION I. — DYNAMICAL GEOLOGY

DIVISION II. — STRUCTURAL GEOLOGY

PART I

PHYSICAL GEOLOGY

BY

L. V. PIRSSON

TEXT-BOOK OF GEOLOGY

INTRODUCTION

GEOLOGY AS A SCIENCE, AND ITS SUB-DIVISIONS

Geology is that branch of Science which treats of the Earth, comprehensively, as a subject of research and study. It seeks to explain the origin of the earth, especially in its relations to other planets, and to the Solar System of which it is a part; it endeavors to account for its varied surface features, for its atmosphere, the distribution of land and water, its rivers, lakes and seas, its mountains and plains. It studies these features in the light of varied forces and agencies operating upon them, and attempts to show their history during long ages past. It takes account of the materials composing the earth, and, from the remains of plants and animals still existing in the rocks, it aims to present a picture of the successions of living organisms which have existed during past times down to the present.

Geology is essentially an historical science in that it continually seeks to determine the origin of things and the changes which they have experienced. The documents upon which the history is based are written in the rocks of the earth itself and the forms of its surface features; they present a series of incontrovertible records, and, if we would read this history, it is our part to learn to decipher the records correctly. Much of this has been done, but much also remains to be done; it is the aim of this work to present a general account of what has been accomplished. Many writers define Geology as a history of the earth and its inhabitants, as shown by the record in the rocks.

Geological Sciences. — From what has been stated above it is clear that the material treated in Geology is of wide extent, and embraces a great variety of subjects. Hence, with the development of the science, the increasing fund of information gained has become so extensive that different branches of Geology, or geological sciences, have come to be generally recognized as separate

fields for research and study. Some of the more important of these are as follows:

Mineralogy, which deals with the origin, composition, and properties of inorganic chemical compounds, which exist already formed in the earth's crust.

Petrology, which treats of the origin, properties, and relations of the material forming the various rock masses which are component parts of the earth's crust.

Meteorology, the science of the earth's atmosphere and its various phenomena, such as variations of heat and cold, of its moisture, and its movements, as seen in winds and storms.

Paleontology, the science which deals with the life of past ages, as shown by the remains or natural molds and imprints of plants and animals, called fossils, which have been preserved, enclosed in the rocks.

Physiography, the science which treats of the present surface of the earth and seeks to understand the causes of its relief features and the nature of the various agencies which are at work modifying them. It might indeed be called the geology of the present.

Economic Geology, which deals chiefly with the use of the materials of the earth's surface in the service of mankind, and in the application of geological facts and principles in obtaining them.

While the recognition of these branches of science, which have developed from the main stem of Geology as separate lines of inquiry and study, has narrowed that of Geology proper, so called, it must yet be understood that they are really special phases of the subject, intimately related to it, and that some knowledge of them is necessary for a proper comprehension of Geology in its broader aspects.

Sub-divisions of Geology. — Very briefly stated, Geology may be considered thus. A mass of varied materials has been, and is being, acted upon by certain agencies, by which definite results have been, and are continuing to be, produced. We may study and determine the nature of the materials operated upon; we may consider the kinds and modes of operation of the agents and forces; and, lastly, we may learn the character and extent of the results achieved. From this it naturally follows that there are three main sub-divisions of Geology, as follows:

DYNAMICAL GEOLOGY, a consideration of the facts and principles concerning the various dynamical agents, such as wind, running water, moving ice, volcanic activities, etc., which operate upon the earth, and modify its outer portion.

Structural Geology, an account of the nature, properties, relations and positions of the component rock masses of the outer part of the earth. It includes the architecture of the outer shell of the earth. These two, dynamical and structural geology, as opposed to historical geology, may be classed together under the general heading of *Physical Geology.*

Historical Geology, a review of the sequence of the events which have happened to the earth in the past, as revealed by the rocks and fossils. This includes *Paleogeography,* or the varied dispositions of land and sea and their character in former ages, and *Paleontology,* which has been mentioned above as picturing the different successions of organic life which have inhabited the earth.

It is clearly evident that a knowledge of structural and dynamical geology is requisite for a proper understanding of the historical portion of the subject and must therefore precede this. From the purely philosophic side it would seem natural to inquire into the character of the masses operated upon before engaging in the study of the forces modifying them, but it is impossible to treat structural geology without some reference to dynamical geology; to consider results without considering causes. Moreover, the various agencies which have worked in the past are at work now, and their operations are in some degree familiar to all. By thus treating dynamical geology first the mind is led from the known to the unknown, and from the present to the past. It therefore appears more logical for the beginner to study dynamical geology first, even though this may cause some repetition in succeeding phases of the subject, and this order has therefore been adopted in this work.

Method of Geological Study. — In former times it was thought that the more prominent and striking features which relieve the earth's surface were due to some sudden and violent action. Thus in surveying a deep canyon, or gorge, scoring the earth's surface, or a towering rock mass giving rise to a mountain peak or tall cliff, it was customary to say that this must have been "caused by some great convulsion of Nature" and this idea with its phrase still persists, and is frequently used by those untrained in geology. It is often seen in descriptions of natural scenery. A great convulsion of nature is a *cataclysm,* and it was thought that the varied changes which the earth's surface has evidently undergone were due to a series of cataclysms, produced by some sort of unknown and terrible forces. The error in this method of thinking is that the element *time* is not taken into account. A given result may be equally achieved by a great force acting very quickly, or by a small force acting through a long period of time. It is the triumph of Geology, as a science, to have demonstrated that we do not need to refer to vast, unknown, and terrible causes the relief features of the earth,

but that the known agencies at work today are competent to produce them, *provided they have enough time.* Thus, we know, for reasons we shall see later on, that the gorge seen in the accompanying illus-

Fig. 1. — Grand Canyon of the Yellowstone River.

tration, Fig. 1, has been cut into the earth's surface by the scratching of the sand and gravel dragged along by the river during the lapse of a vast length of time. Therefore the method of geological

research may be defined as *an inquiry into the past in the light of the present*, of the solving of the unknown by the application of the known.

Geologic Time. — The recognition of the element of time has been stated above as of fundamental importance in geological reasoning. Yet this generally involves a new conception to one beginning the study of the science. As in taking up the study of Astronomy one has to gain new ideas of distance, and to think no longer on a basis of feet, yards, and single miles, but in terms of millions of miles, so in Geology one is compelled to think in vast lapses of time, which in many cases are to be measured in millions of years. Since we have no accurate measures of time in Geology, as we have of distance in Astronomy, the phrase "speaking geologically" is often used with "great" or "small," "long" or "short" to indicate relative lapses of what, from the human standpoint, may be enormous periods of time. Thus, speaking geologically, a million years may be relatively a short interval.

Basal Sciences. — A subject so comprehensive as Geology is largely based upon and has close relations with other sciences. The most fundamental of these are Chemistry and Physics, some knowledge of which is essential. Some acquaintance with Mineralogy is also highly desirable, though in a measure the want of this may be supplied during the consideration of the subjects to which it applies. On the cosmical side Geology passes into Astronomy, and in the study of Paleontology familiarity with the elements of Zoology and Botany is needed. Other subjects, such as Geography and Mathematics, might be mentioned, but it is assumed that the student has already acquired as much of these as is needed.

DIVISION I. — DYNAMICAL GEOLOGY

CHAPTER I

GENERAL CONSIDERATIONS; THE ATMOSPHERE AND ITS WORK

Dynamical geology is a consideration of the facts and principles relating to the different agencies which are now modifying the surface of the earth. They may be broadly divided into two main groups; *external* — those whose controlling energy is derived from sources exterior to the earth, chiefly from the sun and in lesser degree from the moon; and *internal* — those whose operations appear to be due mainly to the interior heat and to the gravitative force of the earth. They may be classified as follows:

External Agencies	Internal Agencies
The Atmosphere.	Underground Water.
Rainfall and Streams.	Volcanoes.
Lakes.	Earthquakes.
The Ocean.	Slow Movements of the Earth's Crust.
Snow and Ice.	
Organic Life.	

Rate of Work. — When it came to be appreciated that these known agencies were sufficient to have produced the present relief features of the earth, and the varied structures of its outer shell, as investigation has revealed them, in a natural reaction from the previous ideas that these were due to successive cataclysms, a view arose that these agencies had always worked with great uniformity, at the same rate and with the same intensity that they do today. This view is no longer held, as it appears that in some periods in the past the action of some of them has been more intensive than in other periods, and it seems probable that, while on the whole the energy has been declining, that of some has been gradually increasing. The reasons for thinking this will appear in the course of this work, as the different subjects are taken up.

The actual rate at which geological work is accomplished, from the human standpoint, is, in general, very slow. Of course in some cases, as where in a volcanic eruption, a very large amount of matter

is suddenly transferred from the inside to the outside of the earth, the work done is not only evident, but startling. The same would be true for instance in the case of heavy landslides. But, in general, the amount of work done at this rate is small, compared with that accomplished, much of it imperceptibly, most of it so slowly, that it is only in viewing the results achieved that we can truly judge of its extent. As in looking at the hour hand of a clock we see no perceptible movement at a given instant and yet know by comparison the movement is taking place, so we infer that many geological processes have been very slowly, but none the less steadily and ceaselessly occurring. It is the recognition of this that forces us to acknowledge the lapse of immensely long periods of time, as previously stated in the introduction.

The Atmosphere and its Work

Character and Composition. — The atmosphere is the outer gaseous envelope of the earth. Owing to the compressibility of gases it is densest at sea-level, where it exerts an average pressure of nearly 15 pounds to the square inch. It regularly decreases in density as one ascends, but its height is not known; however, since meteors passing through space, on coming in contact with it, become heated and luminous, and exhibit this phenomenon at least 100 miles above the earth, it certainly extends upward to this point in appreciable quantity and in more diffuse form to considerably

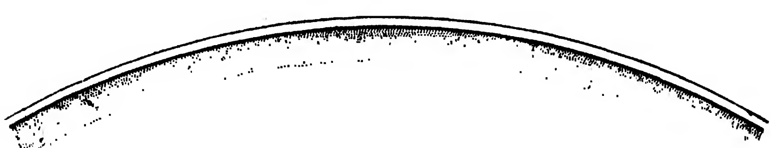


Fig. 2. — Diagram showing a segment of the earth with the atmosphere 50 miles high in true proportion.

greater heights. At 50 miles it is extremely rare, and at about 3.6 miles (19,000 feet) its density is only one half that at sea-level, that is to say one half of the actual amount of air lies below this level.

In composition the air consists of about four parts of nitrogen to one of oxygen. Although these are the chief elements there are also carbonic acid gas, CO_2, in the proportion of about 3 volumes in 10,000 of air, and water vapor whose quantity varies according to temperature, locality, and season; under ordinary conditions in our living rooms a cubic yard of air carries from 1/5 to 2/5 of an ounce of water, or from about one to two tablespoonfuls. In addition there are relatively minute amounts of other gases and volatile

compounds in the air, but these are not of geological importance, and may be disregarded in this connection.

Origin of the Atmosphere. — A discussion of the origin of the atmosphere must in some measure involve that of the earth itself, and while it is inadvisable to consider the latter until later, when the student is better prepared for it, the following considerations are of interest in this connection. Of the different views which have been held regarding the atmosphere's origin no one has, as yet, received recognition as fully satisfactory. They may be roughly classed into two groups. According to the first, the origin of the atmosphere dates back to that of the earth. It is held that the matter composing the earth was once a great mass of extended, heated gas and vapor, part of a larger mass which formed the solar system. As this cooled and contracted it eventually produced our solid earth, but the part which still remained gaseous now forms our atmosphere. Thus the latter is thought to be coeval with the earth.

According to the other view the earth had originally little or no atmosphere; the gases which compose it being held occluded, that is absorbed, in its mass, and as the earth has contracted, either through cooling and crystallizing or through gravitative force, they have been excluded, squeezed out, and now form the atmosphere. This view, in part, might be illustrated by the action of silver which, when melted, absorbs oxygen from the air and holds it occluded; when it solidifies the gas is again returned to the air with some violence.

Following the first view the atmosphere, especially its content in carbon dioxide, has been gradually diminishing in amount; following the second it has been gradually supplied. Various modifications of these views, especially endeavoring to account for variations in the amount of oxygen, water vapor, and carbon dioxide, which are the substances chiefly important as agents in geological processes, have been suggested. Thus for example it has been held, since vegetable life takes carbon dioxide from the atmosphere and decomposes it, storing up carbon and liberating oxygen, that originally the atmosphere was full of carbon dioxide and deficient, or wanting, in oxygen, but that through this action of plants the conditions have been gradually reversed. The student should, however, remember that these views are hypothetical, and that science is not yet able to pronounce authoritatively upon them. Where they concern the aspect of special questions they will be considered in detail in their appropriate places.

Importance of the Atmosphere. — The atmosphere is an agent of the highest importance in surface geological processes. Not only does it work directly in both a destructive and a constructive way, but without it there could be no work from rainfall and running water, as we now know it, and the activities of plant and animal life would cease. Water, without at least an atmosphere of water vapor above it, could not remain on the surface of the globe, which would then be dead and inert, and surface changes, due to external agencies, would not occur. This is illustrated by the moon, which appears to have no atmosphere or water upon it, due apparently to the fact that its mass is not great enough to exert sufficient force of gravity to retain around it the gases which might have formed its atmosphere. Its surface features, as revealed by the

most powerful telescopes, seem to be those produced by internal agencies, largely volcanic in nature, and by the impact of meteoric bodies from space, unmodified by later changes due to atmospheric effects.

Movements in the Atmosphere.— The unequal heating of the atmosphere in tropical and polar regions gives rise to movements in it, which cause circulation on a large scale. Heated in the tropics the air expands, rises, and flows off toward the poles; it then cools, contracts, and becoming denser sinks, and moves back to the tropics. The principle is the familiar one of convection currents in fluids. The circulation thus established, poleward above and equatorward below, is, however, greatly modified by the rotation of the earth, which deflects the north and south movements, or air currents, eastward and westward, giving rise to belts of prevalent winds, parallel to the equator.

North and south of the equator are belts, extending to 28° of latitude, of so-called *trade winds*, which blow in the northern belt from the northeast, in the southern belt from the southeast. They are steady, dry winds of from 10 to 30 miles an hour, not often changed by storms. Where they meet along the equator there is a narrow belt of calms, with occasional light breezes. In passing from colder to warmer regions the air expands and its capacity to absorb moisture increases. Due to this warm dry nature of the trade winds, therefore, the lower lands of the continents lying in their belts have an arid climate and desert character, like Sahara and western Australia, but mountainous regions, especially on the eastern side, like the central Andes, are well watered.

North and south of the belts of trade winds in each hemisphere is one covering the temperate regions in which the winds are prevailing *westerly*. They are of variable strength, from 10 up to 60 miles an hour, and their regularity is much interfered with by great whirls, or eddies, known as cyclones, moving in a general easterly direction, which give rise to storms. These westerlies and their storms determine the climate of most of the United States and southern Canada.

The orderly courses of the atmospheric circulation described are however considerably modified by the arrangement of the continents and oceans, and by the change of seasons from summer to winter. The latter causes a shifting of the wind belts northward or southward, while the unequal heating of the air over land and sea areas by the sun also has its effects, as in local winds such as land and sea breezes.

Air movements about the poles are less well known, and of lesser importance, from economic and geologic standpoints.

Work of the Atmosphere. — It has been stated above that the work of the atmosphere may be regarded as both destructive and constructive. The former consists in its *chemical* action upon rocks and minerals, whereby former chemical compounds are broken up

and new ones formed in their places, and in its *mechanical* activity by which material driven by the wind is not only transported but abrades and wears away exposed rock surfaces. Its chemical action is so greatly aided by water coming in the form of rain and by the expansive power of frost that it is difficult to separate these agencies and they will consequently be considered later under the general term of *weathering*. The constructive work is performed by the wind, which is a factor of considerable importance in transporting and depositing material. This classification may be shown in a table as follows:

WORK OF THE ATMOSPHERE

Destructive { Chemical, Decay of Rocks (Weathering).
Mechanical, Wearing of Rocks (Wind-driven Sand and Waves).

Constructive, Transport and Deposit, Formation of Dunes, Loess, etc.

Destructive Work. — Omitting for the present the work of weathering and of the waves, which are better considered in con-

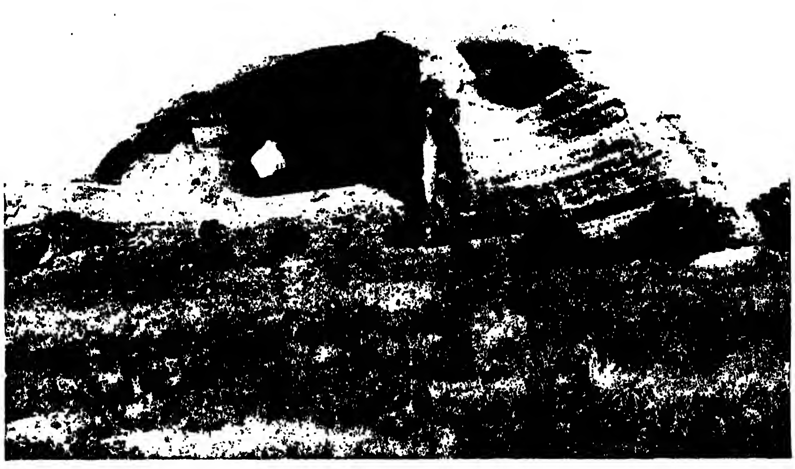


Fig. 3. — Looking Glass Rock, near La Sal Mts., Utah. White horse near tree gives scale. Cut and worn to its present shape, in part by the action of the wind. W. Cross, U. S. Geol. Surv.

nection with that of water, the direct destructive effects of the atmosphere as a geological agent are best seen in those places where sand

driven by the wind wears away exposed rock surfaces. In humid regions, where the rainfall promotes the growth of abundant vegetation, the soil is protected, the wind is unable to lift and carry it, and thus having no tool to work with, its abrasive effects are negligible, or wanting. Moreover, in such regions exposed rock surfaces are less conspicuous, and are apt to be covered by a mat of plant life which serves as a cushion to protect them. In arid regions on the contrary, where there is little or no rainfall, vegetation is scanty or lacking and the loose soil is constantly being shifted by the wind and driven against the exposed rock-masses. This is, of course, most strikingly seen in deserts. In such places rocks or bowlders outcropping from the soil are worn and polished by the sand drifting past and over them. In arid countries, as in the southwest part of the United States, the walls of rock masses are carved and cut into hollows and caves by the disintegration of the rock by chemical and physical processes described later, and the removal of the loosened material by the wind. See Fig. 3. The pounding of sand grains also aids in wearing away the softer parts of the rock leaving the harder ones projecting, often in intricate fret-work. Thus the wind helps in the general process of rock decay by carrying material away, and exposing fresh surfaces to the attack of both wind and weather. The efficiency of the wind as a factor in the wearing away of land surfaces and transporting material in arid regions has probably been undervalued.

The *rate* at which cutting is carried on under favorable conditions may be faster than would at first be imagined. We may gain some idea of it from the fact that the window glass of houses along seashores, which are directly exposed to storm-driven sand, may lose their transparency in a day or two and be completely penetrated in a month or so. It was the observation of this that led to the use of the artificial sand-blast as an instrument for the etching of glass and stone. Telegraph poles planted in the desert are quickly cut down by the sand drifting past their bases. The chief destructive work of the wind, however, is not so much in actually abrading surfaces, as in removing material loosened by other means.

Constructive Work. — This is illustrated in the deposits formed by the wind from transported material. A gentle breeze lifts and carries dust, a strong wind drives sand along with it, while a tempest may move gravel the size of peas. There may be transported in this way vast quantities of material. See Fig. 4. For instance, it has been shown that a single storm, travelling from the arid southwest a thousand miles into the region about the Great Lakes,

brought with it a million tons of dust, and probably a much larger quantity, which was deposited in the snowfall over a wide area. Such material, dropped as the wind slackens, under favorable conditions, may form deposits of great magnitude. They are known

Fig. 4. — Sand-storm sweeping over Khartoum North; in front is the Blue Nile. Shows enormous transporting power of the wind. Soudan, June 6, 1906. (Photo by Wm. Beam, M.D.)

as *eolian* (Æolus, god of the winds) deposits, a term used to distinguish them from sedimentary deposits formed in water. They are most prominently illustrated in dunes and in the loess.

Dunes. — Sand-hills, or dunes, are hillocks, or hills, made by wind-borne sand in a manner similar to that in which snow forms drifts. They vary in height from a few feet up to 100, or even 200, feet or more. The sand grains composing them are mainly of quartz,* though a variety of other minerals may occur, rounded by the rolling and abrading action they have undergone. The starting of a dune may have been caused by some obstacle, such as a stump or stone, causing a temporary lull in the wind behind it. Sand is here deposited and the dune, once begun, continues to grow. In regions where they occur the erection of buildings has in this way started their formation. The surface of a dune is very apt to be covered with fine parallel ridges of sand an inch or so in height, transverse to the direction of the prevailing wind, and called *ripple-*

* If the student is not acquainted with the ordinary rock-minerals he may gain such acquaintance with them as is necessary in the study of this work by referring to Appendix A.

marks, because they are similar to the fine parallel ridges made on sandy bottoms by the action of waves. See Fig. 5. Dunes are found along low coast lines in all parts of the world, where the sand made by the waves is washed ashore, and, caught up by the prevailing winds from the ocean, is drifted inland and accumulated. Thus they occur at various places along the Atlantic coast, and on the Pacific

Fig. 5. — View of sand-dunes, near Mammoth Station, Cal., showing ripple-marks. W. C. Mendenhall, U. S. Geol. Surv.

shore of the United States; in England; on the shores of the Baltic Sea; in Holland, France, etc. In the same way they are produced on the shore-lines of large lakes or inland seas; thus the southern end of Lake Michigan is fringed with high sand-dunes.

In arid regions where the soil, formed by the disintegration of the underlying rocks, is not held down by a sufficiently protective mantle of vegetation and is therefore easily moved by the wind and accumulated in favorable places, sand-dunes are a common phenomenon. They are thus characteristic features of desert landscapes, and the great deserts of central Asia, of Africa, of Australia, and those in western America are in considerable part covered with them. The areas from which the soil is moved are left as barren stony wastes.

Shape of Dunes. — The shape of the dune varies according to local circumstances and is commonly irregular; one form called a *barchane* is seen outlined in the ground plan in Fig. 6. The arrow

shows the direction of the prevailing winds. The windward side *a* has a gentle slope whose angle depends on the average strength of the wind; if it is very strong the sand will be carried up a steeper angle of slope. The dune is terminated by a rather sharp crest. On the leeward side *b* is a relative calm with a back eddy and the sand is here dropped; the angle of slope is here much steeper, being that at which sand will lie at rest without sliding down, from 20° to 25°,* the down-sliding being, in part, arrested by the eddy. From this ideal condition the shape is being constantly modified more or less by shifting winds.

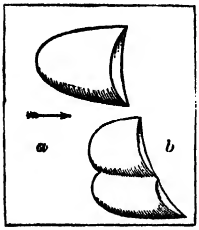


Fig. 6. — Shapes of sand-dunes, called barchanes.

Migration of Dunes. — The transference of material from the windward to the leeward side causes dunes to march steadily in the direction of the prevailing wind, unless the sand is held down by a mat of vegetation. As the sand is lifted by the wind and then dropped, the dunes maintain their height, or, with increase of material, grow higher. Along exposed coasts the prevailing winds are from the sea and thus the shore-line, especially where low and sandy, is apt to have a fringing belt of sand-dunes which may vary from a few hundred yards, or less, to a number of miles in width. They tend constantly to move inland, the rate of movement depending on the force of the wind; in Denmark they have been found to move as much as 24 feet in a year, in other places 15 feet or less.

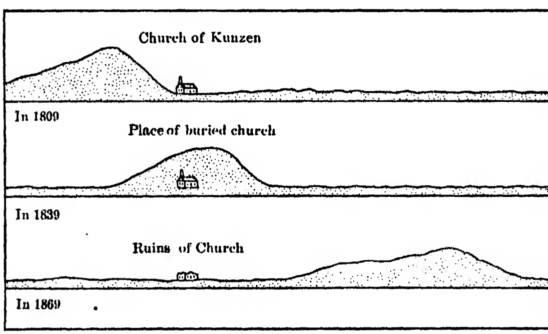


Fig. 7. — Movement of a sand-dune during 60 years on the east shore of the Baltic Sea at the village of Kunzen. (After Berendt.)

* The steepest angle of repose that could be obtained by carefully pouring dry dune sand from San Francisco was about 30°, in dunes this is probably not often obtained.

In their march they cover and destroy arable lands, forests, and even villages and towns, leaving ruined sandy wastes behind them. Many instances of this could be cited from various parts of the world; some of the best known are from the shores of the Baltic Sea. See Fig. 7. In the deserts of central Asia Sven Hedin, the explorer, found ruined cities of an ancient civilization emerging from the sand, which a long period ago had overwhelmed them and the fertile lands which must have once supported them.

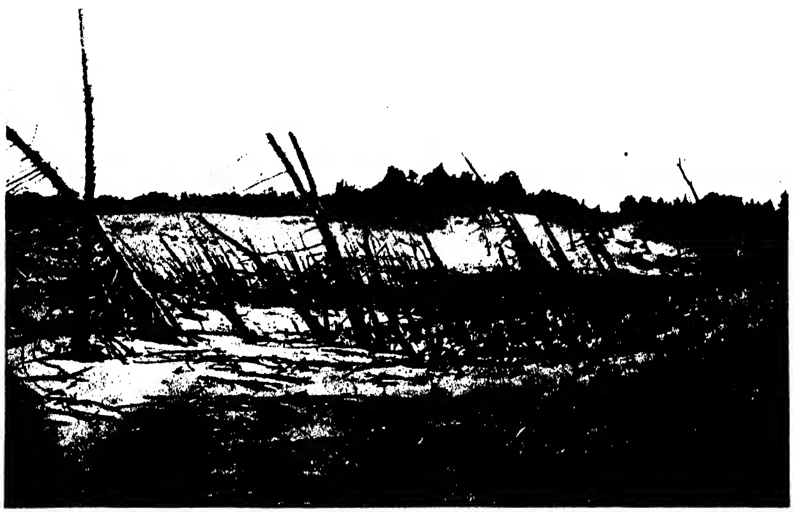


Fig. 8. — Forest overwhelmed, covered, killed, and then left exposed by marching sand-dunes. Manitou Island, Lake Michigan. I. C. Russell, U. S. Geol. Surv.

When covered with vegetation the dunes are stationary, or move more slowly, and therefore when they become a menace attempts are usually made, and often successfully, to induce such a growth upon them. This has been done in places on the Pacific coast, and it is stated that the effect of starting forest growth on the dunes along the coast of France to render them stationary resulted, not only in accomplishing this purpose, but so profitably in regard to the forest itself, as to greatly help in inducing reforestation elsewhere.

Loess. — In the valley of the Rhine and other rivers of northern Europe there occur in places considerable deposits, on the valley sides, and even up to great heights on the slopes of mountains, of a peculiar structureless, yellowish-brown earth to which the name of *loess* has been given. The particles of quartz, feldspar, clay, cal-

cite, mica, and other minerals * composing it are much finer than those of ordinary sand and are sharply angular, showing no sign of rounding by wear as the larger grains carried by wind and water do. Nor do the deposits exhibit the lines of stratification, or bedding, which are characteristic, as will be shown later, of the sediments laid down by water. Moreover the shells found in it are those of land forms, like snails, and the bones those of land animals. These facts, and its irregular distribution at various heights, appear to prove that it is a deposit which was formed on land, not in water.

The loess is full of small, slender, perpendicular holes, or tubes, which give it a vertical cleavage, so that it commonly presents in many places upright bluffs along ravines and river courses, which, depending on the thickness of the deposit, may be of considerable height.

Similar deposits are found in the United States in the central part of the Mississippi valley, especially in the states of Iowa, Kansas and Nebraska, and covering in sum total thousands of square miles. They also occur in the states of Oregon and Washington and other parts of the western United States. The thickness is usually not great; from 10 to 20 feet perhaps, sometimes as much as 100.

It is now generally believed that the loess of Europe and America is for the most part an eolian deposit, dust blown and dropped in favoring localities by the wind, and accumulated during long periods of time. The origin of the material is supposed to be as follows: It is known that in a recent period, as will be shown later, large areas of North America and Europe were covered with thick and moving sheets of ice which ground up the underlying rock and soil. The fine material thus produced was carried outward and beyond by waters resulting from the melting of the ice, and when spread out in the open valleys and land stretches it was, when dry, whirled away in dust clouds by the wind and deposited. The stems and roots of successive generations of grasses growing on the deposits and buried by the rising accumulations have by their decay produced the slender vertical tubes which have been mentioned above as occurring in the loess.

The greatest development of the loess is in Asia, in Turkestan, Mongolia, and especially China. The greater part of northern central China is covered with it, and the yellow earth washed down by the rain and streams colors the waters of the great river Hoangho (Yellow River), and the sea (Yellow

* See Appendix A for description of these minerals.

Sea) into which it discharges, and has thus occasioned their names. The bluffs, which it forms, are in places 500 feet high, and its thickness is estimated to be greater than this in some parts. In the river valleys it commonly forms a series of terraces, rising step-like above one another, with upright bluffs facing the river. The Chinese, who cultivate the arable soil it forms, have cut back into these bluffs and fashioned cavelike dwellings for themselves, which have been inhabited for centuries, as seen in Fig 9. Owing to the vertical cleavage and softness of the loess the streams, even small ones, run in steep-walled gorges, while the roads and paths which have been used for centuries, by the rapid wear of the soft material and its constant removal, when

Fig. 9. — Dwellings in the Loess in Shansi, China. Photo by Bailey Willis, U. S. Nat. Mus.

thus loosened by wind and rain wash, have also become small canyons. The whole country is thus dissected by innumerable ravines and gorges, which render it impassable to the traveler, unless accompanied by a guide.

The loess of China was held by von Richthofen, the German geologist and explorer, to have been produced by dust, continually borne from the great deserts of central Asia during long ages by the prevailing winds, and deposited in the basins and valleys where it now lies. Some hold, however, that the loess, both here and elsewhere, is in large measure, if not entirely, a deposit made by water.

Other geological effects of the atmosphere in accumulating deposits of volcanic dust, of tornadoes levelling forests and thereby impeding drainage, etc., might be mentioned, but these are of less importance. The phases described illustrate sufficiently its mechanical work and we are now ready to consider its chemical action,

especially when aided by water acting both chemically and mechanically. This is seen in the phenomenon called weathering.

Rock Weathering and Soil Formation

The Soil Mantle. — The outer shell of the earth, as we know it, is everywhere composed of more or less firm solid rock, commonly called for any particular place "country rock" or "bed-rock." Nearly everywhere this is covered by a mantle of loose material of variable thickness which passes under a variety of names, but which for convenience, where exposed to the air, we may designate as "soil." Here and there in ledges, precipices, and the craggy tops of hills and mountains, we may see the bed-rock projecting above this mantle of soil. As compared with the earth, as a whole, it is a mere film on its outer surface and might be compared to the film of tarnish a polished metal ball would acquire on exposure to moist air. The part which it plays in geological processes will be considered later; it is our purpose now to study its origin, for in its formation is seen one of the most important functions of the atmosphere as a geological agent.

Weathering. — The outer rocky crust, or bed-rock, is everywhere more or less shattered; it is penetrated in all directions by cracks and fissures, some great, some small. Even the mineral grains are more or less filled with cracks, often cleavage cracks. Into such fissures the air enters, carrying with it the various gases and the insensible moisture it contains. If the moisture becomes sensible, as in the form of rain, then water enters them and by the force of capillary attraction may be drawn into the most minute crevices. Since the air contains water, and water, as a liquid, has the power of dissolving gases, and therefore contains those of the air, the work of these agencies, air and water, is so closely associated that we cannot draw any sharp line between them. They work together to cause rock to decay and turn into soil, and in this they are powerfully aided by changes of temperature, by heat and by cold, by substances carried in solution, and to a lesser degree by the action of plants and animals. The work is partly mechanical, partly chemical, and taken altogether it comprises a rather complex set of processes which are conveniently designated under the name of *weathering*. Some of these may be considered separately.

Heat and Cold. — The daily range of temperature, the difference between the heat of day and the cold of night, may be 50° or even as much as 75°; the annual range, between the cold of winter and the heat of summer, may be 100°, or even as much as 150°. Where

the rock masses are exposed to such changes of temperature they are powerfully, irresistibly expanded and contracted, see Fig. 10. A mass of granite 100 feet long by a change of 150° would expand one inch. Moreover the unlike mineral grains composing most rocks do not expand equally, and hence interior stresses are produced. Unable to withstand such actions the rocks are ruptured and break into smaller pieces. Such effects are not felt deeply, for rocks are poor conductors of heat, and thus when bed-rock is exposed the

Fig. 10. — Buckling in sandstone layers due to expansion from heating by the sun. Wyoming. E. E. Smith, U. S. Geol. Surv.

back and forth expansion movements of the surface layer tend to shear it loose from the unchanging mass below. Thus the surface crumbles, or layers scale off, or exfoliate, as seen in Fig. 11. By this process, in those places where great extremes of temperature occur, as in deserts and in semi-arid regions, the exposed rock masses are broken, rounded off, and disintegrate into soil and gravel.

This process breaks up the rock mechanically without chemically changing the constituent mineral grains and is known as *disintegration*. It may be aided to some extent by the deposition of salts in the pores and cracks in the rocks, since in arid regions the former tend to be drawn to the surface and left by evaporation. Then comes the wind which carries the finer material away, as explained in a foregoing section.

Effect of Frost. — In cold countries the effects of disintegration described above are greatly aided by the action of frost. Water fills the crevices and on freezing expands, splitting the rocks with great force. This action is best seen in high mountains whose slopes

Fig. 11. — Exfoliation, or scaling of rock, by alternate expansion and contraction of surface layers. Nevada City, Cal. G. K. Gilbert, U. S. Geol. Surv.

are in different places, and sometimes entirely, covered with such broken rock fragments, commonly called "slide-rock." Where such masses of débris accumulate at the foot of a cliff they are called *talus,* as seen in Fig. 12. In high mountain ranges the effect of frost in carving and shaping the peaks and pinnacles of rock is very great.

The term *slide-rock* implies any loose fragmental rock lying on a slope, while *talus* is restricted to those cases where there is a projecting mass, or cliff, of country rock above from which the débris has evidently been derived.

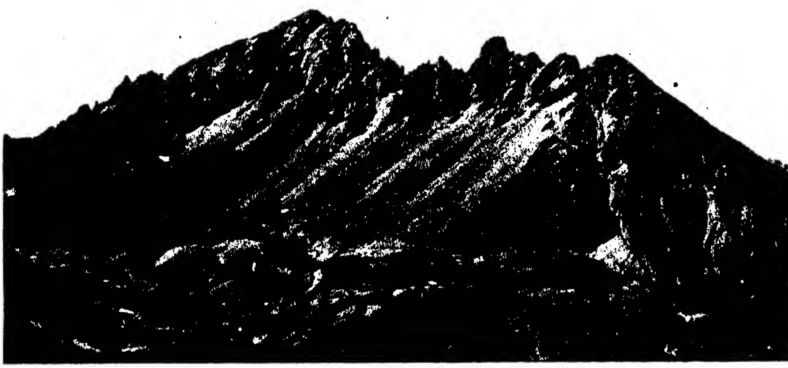


Fig. 12. — Rock disintegration and weathering in high altitudes, with formation of long talus slopes of slide rock. Mt. Sneffels, Colorado. W. Cross, U. S. Geol. Surv.

A talus should not be conceived as having a section like that of *abc* in Fig. 13, a case which can rarely happen, but rather like that of *a′b′c′*. A talus indeed is often only a rather thin sheet of fragmental material resting on sloping bed-rock, which may here and there project through it. As the destruction of the cliff *a′* goes on it may retreat until its contour is like that of *b′c′* beneath the talus. It may also be covered with the rising talus until the latter forms the whole slope of the mountain. Ordinarily coarse material, blocks of rock, is seen at the top of the talus slope; as this breaks up into finer it is washed down, descends, and may gradually assume a more gentle slope; this lower part is frequently made of soil with vegetation growing on it. In warm regions it is chiefly the expansion and contraction which breaks the bed-rock and forms the talus; in cold countries the action of frost is more important.

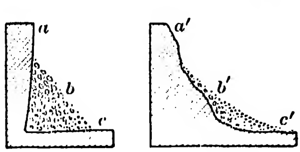


Fig. 13. — Section through a cliff and its talus.

Chemical Work in Weathering. — The mechanical breaking up of rock and its conversion into soil is powerfully aided by chemical processes. In these water, oxygen, and carbon dioxide are the

Fig. 14. — Talus cone at the foot of a gulch. Foot of talus to mountain top is 3000 feet in vertical height and over a mile in distance. Mt. Ætna, Colorado. R. D. Crawford, Geol. Surv. of Colo.

chief agents. By them the chemical compounds forming the minerals of the rocks are attacked and in a great measure changed into new substances. The oxygen converts those of a lower state of oxidation into ones of a higher; water, besides being a solvent, enters into combination in many new compounds; carbon dioxide, with the water, helps to bring substances into solution and to change them into carbonates. Thus in a general way we may say that as a result the new minerals formed in the place of the old ones are more highly oxidized and contain water or carbonic acid.

This may be illustrated as follows: One of the most important of the rock-making minerals is feldspar * of which there are several varieties; one of these known as orthoclase consists of oxides of silica, alumina, and potash. When this is attacked by water containing carbon dioxide in solution the following reaction takes place.

Orthoclase	+ Water	+ Carb. diox.	yields Kaolin	+ Quartz	+ Potas. Carb.
$2\ KAlSi_3O_8$	$+\ 2\ H_2O$	$+\ CO_2$	$=\ H_4Al_2Si_2O_9$	$+\ 4\ SiO_2$	$+\ K_2CO_3$

This is one of the most important reactions which takes place in nature, since the existence of life is largely dependent upon it. Animal life depends on vegetable life, and the latter upon the soil; kaolin — commonly called *clay* — is an essential ingredient of good soils, while carbonate of potash is a necessary food of plant life; by this process the potash in the rocks is removed from the feldspar, converted into a soluble form, and vegetation is able to assimilate it.

When the component minerals of a rock are changed by chemical actions into new minerals, as orthoclase into kaolin and quartz, the process is spoken of as *decomposition*, and it may be contrasted with the *disintegration*, previously mentioned, in which rocks are mechanically crumbled without chemical change. Generally, both processes work together.

Solvent Action of Carbonic Acid. — Some rocks, such as limestone, are composed almost entirely of calcium carbonate, $CaCO_3$, which forms the mineral known as *calcite*, while in others this substance acts as a cement to bind the grains to one another, as in some sandstones which are made of grains of quartz sand thus held together. Calcium carbonate is nearly insoluble in pure water, but when carbon dioxide gas, CO_2, is dissolved in it there is formed an aqueous solution of carbonic acid, H_2CO_3. This attacks the calcium carbonate and converts it into calcium bicarbonate, $H_2Ca(CO_3)_2$, which is quite soluble in water. The natural surface waters, like rain, contain more or less carbonic acid in solution and more is supplied by decaying vegetation; through its action the binding material is dissolved, the grains loosen, and the rock crumbles and breaks down into soil. In the case of limestone the greater

* See Appendix A.

Fig. 15. — Illustrates the formation of soil in place by rock weathering and decay. The material graduates from firm rock below, through rotten rock and then subsoil, to true soil above. The transition is gradual without break. The true soil above is colored dark by decayed organic matter. G. P. Merrill, U. S. Nat. Mus.

part of the rock may go into solution and be carried away, leaving only the insoluble impurities, usually clay, to remain behind as the resultant soil. This solvent action of carbonic acid on carbonates is one of great geological importance; we are here only concerned with it in so far as it helps to make soil; what it accomplishes in other ways will be treated in a later place.

Soil in Situ. — The process of weathering is superficial and is very slow; if the bed-rock were perfectly firm, solid, and continuous it would gradually cease, since the underlying rock would be protected by the mantle of soil upon it. It is a common thing, however, for this mantle to be removed as fast as formed, by agencies which will presently be described, exposing fresh surfaces to attack. Even where this does not happen, the agents of weathering may be able to penetrate quite deeply on account of the fissured and cracked condition of rocks, previously mentioned, and form considerable depths of soil. Where this has taken place, if one examines downward, as in wells or road cuttings, one finds that the soil at the top, supporting vegetation, gradually passes into a more or less coarse, gravelly material full of angular bits of rotten rock; this is known as the *sub-soil*. The latter passes downward imperceptibly into decayed rock which crumbles more or less easily and this in the same gradual way into the firm solid, unaltered bed-rock. Thus there is a gradual transition from soil above to rock below and this proves that the soil has been formed in the place where it now lies by the decomposition of the local rock. Thus these changes can be conveniently divided into the four stages mentioned: *a*, soil; *b*, sub-soil; *c*, altered rock; *d*, unchanged rock. When the soil lies where it has been made it is termed "in place" or soil *in situ*. An illustration of this gradual change from rock below to soil above may be seen in Fig. 15.

The reason for making this distinction as to whether a soil has been formed *in situ*, or not, is important because over wide areas the soils are not in place, but have been brought from elsewhere, or shifted, by the action of the wind, running water, moving ice, etc., as illustrated in Fig. 16. Over much of the northern United States, Canada, and northern regions generally,

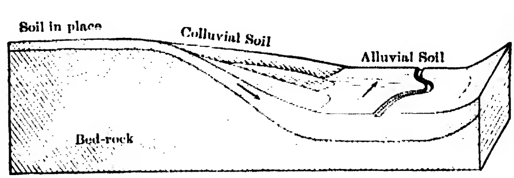


Fig. 16. — Diagram illustrating the forming and movement of soil.

it will be found that there is no gradual transition from soil to rock, such as described above, but that the soil rests directly upon unchanged solid bed-rock. This is a clear proof that the soil has been shifted. These regions were once covered, as will be shown later, by vast areas of moving glacial ice, which ground away the rotten rock and shifted the soil. In the southern states and in warm and tropical countries much of the soil is *in situ,* and in some places it is as much as several hundred feet deep.

Kinds of Soil. — The nature of the soil produced by the decay of rocks depends chiefly upon the kinds of mineral grains of which they are composed. The more important of these minerals are *feldspar, quartz, calcite* and *clay,* which have been mentioned previously and their compositions given. Feldspar changes to clay, whereas quartz, SiO_2, is not affected by weathering. Calcite, $CaCO_3$, is soluble under the conditions which have been stated. In addition to these there are many other kinds of minerals, such as the silicates of iron and magnesia forming substances like hornblende, dark mica, etc., but these are of lesser importance. Thus when rocks like granite, which is chiefly composed of a mixture of quartz and feldspar, are thoroughly decomposed into soil the latter consists of clay intermingled with quartz grains. A pure feldspar rock would yield only clay; while a pure sandstone would give only sand by disintegration. According to the size of the particles which compose the broken and disintegrated rock the following gradations are recognized: Pieces of loose rock from the size of a small melon up are termed *bowlders;* those larger than peas are called *gravel.* Pieces smaller than peas, but which do not cohere when wet, are *sand,* while the finest material, which can be carried by the wind, is *dust,* and this generally coheres when wet and is termed *silt,* or *mud* or *clay,* according to its character. Ordinary soils are composed of variable mixtures of sand, and these finer materials. We may roughly classify them into the following groups:

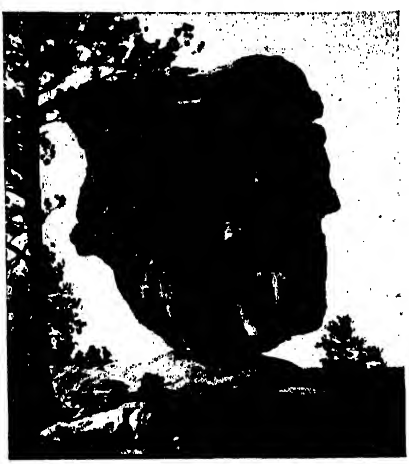


Fig. 17. — Residual bowlder resting on bed-rock, "Balanced Rock," Garden of the Gods, Colorado.

Sand, composed of sand grains, mostly quartz, without clay.
Loam, mixtures of sand and clay.
Clay, the finest material, mostly kaolin, without sand.

Of these loam is most easily worked and makes the best soil; clay is next, but is apt to be stiff and difficult to work, while sandy soils are usually light and also poor for the growth of vegetation.

The red and yellow colors which many soils possess are due to the hydrous oxides of iron produced by the decay and oxidation of the original minerals in the rocks consisting of iron oxides and silicates. A dark or black color, best seen in swampy soils, is due to carbonaceous material, resulting from the decay of vegetation. This substance, which is present to some degree in most arable soils, is known as *humus* and those very rich in it are called *muck*. When a soil contains a considerable quantity of carbonate of lime it is termed a *marl*. Thus *sands, loams, clays, mucks,* and *marls* are the chief kinds of soils and there are all gradations of these into one another. Owing to the presence of the dark organic matter, or to the greater oxidation of the iron compounds, and often to other

Fig. 18. — Residual bowlders left by decomposition and wearing away of bed-rock. The bowlders are included masses of a harder, more resistant material and of rounded shapes (concretions). This shows that residual bowlders may in some cases differ from the bed-rock on which they lie. Coalinga, Cal. R. Arnold, U. S. Geol. Surv.

reasons the top soil is apt to be much more strongly colored than the underlying subsoil.

Bowlders of Decomposition. — The change of bed-rock into soil is not apt to take place equally, either over small or wide areas. For the rock mass undergoing decomposition is not everywhere uniformly cracked and fissured, allowing free access to all its parts of the agents of disintegration and decomposition which have been described. Moreover, some parts of the rock mass may be different in composition and texture from the rest, and thus harder, denser, more durable, or less soluble. From this it commonly happens that the soil is more or less filled with pieces of unchanged or but little altered rock, which are termed *bowlders.* That such *residual* bowlders have been formed in the place where they are now is proved by their similarity in mineral composition and appearance with the still unchanged bed-rock below. But it frequently happens that bowlders are very different in character from the rock below them and this shows in most cases that they have been moved or are *transported blocks.* It may happen that, where residual bowlders of decomposition are forming, the soil about them may be removed by wind or rain wash as fast as formed, as illustrated in Fig. 17. In this case they may be left upon the surface as scattered blocks, see Fig. 18.

CHAPTER II

RAIN AND RUNNING WATER

The Rainfall. — The amount of rainfall which a country receives is dependent on a variety of factors, such as the direction of the prevailing winds; the nature of the places over which they have previously passed, as to whether these are land or water areas, and, if the former, low land, or high mountainous tracts; the surface character of the country which receives them, whether high or low; and on other considerations as well. Thus it happens that the amount of rainfall received by the land is very unequally distributed over the world; in some places, as in Central America, it may be as much as 100 inches per year, while in the great deserts it is less than 10. In general, in North America, one may say that in the Atlantic sea-board region, and in the Southern States, the rainfall is 40 inches or more per year; as one goes westward into the Mississippi valley it diminishes to 30 inches or somewhat more; in the Plains region to 20 or less; in the Great Basin between the Rocky Mountains and the Sierras to 10 or less. Locally in the mountains it is increased, as these are great condensers of moisture. On the Pacific coast it increases again. Roughly speaking one may term those regions where the rainfall is 20 inches or less *semi-arid* to *arid*, those where it is greater than this *humid*. As we shall see later, the work of geologic processes, and the results of this work, are in many ways strikingly different in arid regions from those in humid ones.

The Run-off. — A part of the water which falls in rain is evaporated and passes back into the atmosphere; another part sinks into the soil and the fissured or channeled bed-rock below it, and there, on its way underground to the sea, becomes an internal geologic agency whose work we shall study later. Some of this water, which thus sinks at first, reappears as springs and, joined by that which runs directly upon the surface, finds its way by means of rivers into the sea. This water which the streams carry away from the surface of the land is known as the *run-off*. The immediate part of the run-off is that which causes floods and freshets, while the springs furnish the steady supply. It has been estimated that

there falls annually upon the land areas of the globe about 29,000 cubic miles of rain water, and of this about 6500 cubic miles constitutes the run-off. In the Mississippi basin one quarter of the total rainfall forms the run-off. It is the object of this chapter to describe the geological work performed by this run-off.

Movement of Soil Mantle: Erosion. — As has already been shown, the surface of the land is, in general, covered by a mantle of soil resting on bed-rock. Now by the action of running water, frost, etc., aided by gravity, this mantle of soil and crumbled rock, which, as it ordinarily appears to us, seems to be at rest, is actually in motion, considered from the geological standpoint, and is being continually urged downward into the sea, its ultimate goal. On steep mountain slopes it goes more rapidly, in valleys more slowly, while in level plains, like water in a lake, it is temporarily at rest. Its rate of motion varies from time to time and from place to place. Much of this motion is known as its *creep*. As it moves away, its place is supplied by fresh products of rock decay, which also move in their turn, and so the process is continued, year in, year out. This formation of rock débris and its removal produce the waste of the land surface and this wasting is known under the general term of *erosion*. We may study in detail the various features of the process and the agents which perform it; chiefly they are wind, running water, the action of waves and moving ice; the work of the wind has been already treated; that of ice and the waves will be considered later; the work of rain and running water is to be considered here.

Rain Wash. — It is a well-known fact that the wash of the rain continually carries away the soil, moving it from higher to lower places. The rain drops run together and form rills; these dig out gullies; the gullies run together and the larger volume of water excavates ravines or gulches. These effects are conspicuously seen on steep slopes of soft material, such as clay, and are illustrated in Fig. 19. The result of this removal of material is seen after every storm in the volume of muddy water pouring out of each gully and ravine into the larger channels below. The amount removed in a given time by this means varies greatly with a number of circumstances. For instance it varies with the character of the soil and of the bed-rock. In New England, for example, the bed-rock is hard and crystalline, the soils stony and clayey glacial deposits which resist erosion well; what the rains wash into the streams is almost entirely from the soil, while over wide areas of the Southern States and the Western Plains, the country rock consists of soft,

little compacted deposits of sand and clay, whose resistance to rain wash is not much greater than that of the soil itself, or the soil is loose and deep and held only by the vegetation. Rivers draining these latter regions are constantly turbid and filled with muddy sediment. Another feature which has a great effect upon the rate of erosion, as partly noted above, is whether the soil is covered with vegetation or not, and this is so important that it deserves especial consideration.

Rain wash is really the beginning of stream erosion and should be considered a part of that process, which is treated in detail later. It is introduced here because it is that phase of erosion which is most familiar to all, and may therefore well serve as an introduction to the work of running water.

Fig. 19. — Effect of rain wash in beds of clay. Sioux Co., Neb. N. H. Darton, U. S. Geol. Surv.

Effect of Vegetation on Erosion. — Where the soil supports a rank growth of vegetation, and especially if it has a thick forest cover, erosion by rain wash and gullying is greatly hindered and it may be almost entirely prevented. There are two reasons for this: first, because the mass of roots distributed through the soil, together with the mat of organic matter on the surface, holds the soil firmly in place and enables it to resist the pressure of the moving water, and, second, because the mat of vegetation acting like a sponge absorbs the water and permits it to drain off so slowly that the destructively erosive effect of sudden rushes of water after storms is prevented. Likewise in springtime the rapid melting of the snow is hindered by the forest shade, especially when it is composed of evergreen trees. Such effects are of course most noticeable

on steep slopes, among the hills and mountains. If, in the settlement and cultivation of a country, the forest cover is entirely removed from such places, erosion starts at once and proceeds rapidly, as illustrated in Fig. 20, and in a variety of ways great damage may be done. It is a noticeable fact that in forest-covered countries the flow of the streams is quite regular and their waters relatively clear; in those well cleared of forests and cultivated, the rivers on the other hand are subject, especially in the spring, to sudden and heavy floods, their waters are very muddy, and they are apt to be very low, or even dry, in months of little rainfall.

The regulative action of the forests on erosion and the flow of rivers is a matter of great importance, not only from the geologic standpoint, but as

Fig. 20. — After the removal of the forest cover the soil has been carried away so rapidly that the remaining trees have their roots exposed by the lowering of the surface. Southern Appalachians. U. S. Forest Service.

vitally affecting the economic conditions of civilization. In some countries, of which Spain and northern China might be selected as examples, the improvident removal of the entire forest cover has reduced large areas, through displacement and loss of arable soil by erosion, to sterile wastes, subjected alternately to hot and baking droughts and sudden disastrous floods. Destruction of the forests by fire may have a similar effect. Once destroyed, and the soil washed out, they may not be restored, or only with great difficulty after long periods of time. Considerable areas in the Southern States have been much impoverished in this way. In places, where density of population causes all land that can be cultivated to be valuable, terracing of hill slopes to prevent erosion is much resorted to. The yearly loss of arable soil is one of the great wastes of modern civilization that should be checked as much as possible; forests should be cultivated on all eminences and places not adapted to agriculture and their cutting carefully governed, not alone for the timber they may furnish, but to prevent erosion and regulate the flow of streams.

Erosion in Arid Regions. — In arid and semi-arid regions the effects of erosion, as produced by rain wash and gullying, are perhaps most plainly seen. If the region is absolutely rainless there is naturally no erosion from this cause, but places where there is practically no rainfall are rare; a certain amount of rain falls even in those districts which are usually termed arid, and, as it is apt to come in heavy and violent downpours, its effect is strengthened. The percentage of run-off is increased and with it the erosive effect because the soil contains a larger quantity of air in its pore spaces than in humid regions, and this, when the surface film of soil becomes moistened, prevents the entrance of more water. The lack of an adequate mantle of vegetation also helps the erosive process and permits its effects to be clearly open to our observation. This also allows the wind to perform its part of the work, as described in the preceding chapter, in transporting material from higher to lower levels where it is more accessible to the streams which carry it away, or by dropping it directly into the streams. Thus the wind, which is of small importance in humid regions, becomes a strong factor in erosive processes in arid ones.

Striking examples of such erosion are to be seen along the rivers which drain the Great Plains region. These rivers, such as the Missouri and its

Fig. 21. — Bad-lands, near Scott's Bluff, Neb. N. H. Darton, U. S. Geol. Surv.

tributaries, the Cheyenne, Platte, etc., in places run in valleys sunk a considerable distance below the general level of the country. The country rock which forms the sides of the valleys for the most part is very soft, barely consolidated clays and sands, and thus easily cut by rain wash and gullying. The result is, that on either side of the stream, from the bottom-land by the river to the bench-land forming the plain, lies a gradually rising belt of

country, cut in the most intricate fashion by systems of gullies, gulches, and ravines, with spurs, knobs, and sharp ridges separating them as illustrated in Fig. 21. Such tracts of country are known as *Bad-lands,* from the difficulty experienced in traversing them.

It is to be noted, that, in general, where not merely the top soil but the underlying rock is concerned in erosion, the softer the material, the more striking become the effects of gullying, and the rougher the resultant topography. It is as if, in the hollowing out of a trough from a block of wood with a gouge, a very soft kind of wood were used; then with each stroke the hollow chisel would bite deeply and the intervening ridges would be pronounced. In hard crystalline rocks the rate of erosion is dependent on that of weathering and disintegration and hence, except in very high mountains where these processes are rapid, the forms of erosion are more smooth and subdued.

Remnants of Erosion. — It has been explained under the description of the weathering of rocks that this process was not everywhere uniform. All parts are not equally accessible by cracks and fissures to the agencies which produce decay, and some parts may be harder and more resistant than others. Since erosion consists in the loosening of the rock substance and its removal, it commonly happens in regions undergoing the process that, due to this want of uniformity, there are projecting masses of the more resistant material. This is illustrated in Fig. 22, as occurring on a small scale, but such features are found of all sizes up to veritable mountains. Moreover, erosion is less rapid in areas between streams, because the slopes may be more gentle where the valleys are not cut down, and the material must be transported farther; this applies especially in the level plains country. Large isolated masses are known in the western regions as *buttes* and are illustrated in Fig. 23; they have been generally made in these ways and are remnants of erosion. When such an elevation is broad and flat topped it is termed a *mesa*, from the Spanish, meaning "table" and referring to its table-land character; it is also a remnant of

Fig. 22. — Hard masses of ironstone in beds of soft sandstone have shielded the rock below them from erosion and produced pillars. Monument Park, Colo.

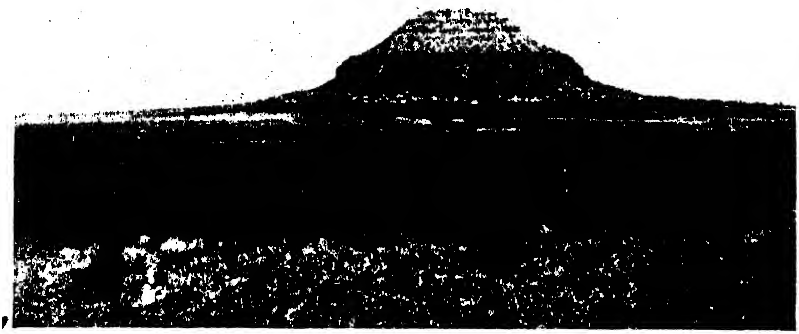


Fig. 23. — Red Butte, Bell Ranch, New Mex. W. T. Lee, U. S. Geol. Surv

erosion. Such mesas are generally capped by a layer of hard rock, often lava, which has protected the softer layers beneath. These features and the rugged sculpturing of mountains all testify to the great work of erosion and the amount of material carried away.

Rivers and River Valleys

Gullies run into ravines or gulches, and the rivulets which drain the latter run together to form brooks and creeks which in turn unite to make rivers. The rivers then are the main channels of drainage, and they are the chief factors in carrying away the waste of the land. They are to be regarded as the great trunk lines of transportation for the products of erosion which are delivered to them by their tributaries. In addition they are themselves powerful agents of erosion; in them the work of running water as a geological agency is most conspicuously displayed, and this work in its varied features and the results of it may now be considered.

Course of a River; its Gradient.— If we should think of a typical river we should imagine it rising in lofty mountains through the union of many impetuous streams or dashing torrents; gathering headway it rolls rapidly through the belt of lower hilly country and emerges upon wide plains through which it wanders in many curves in a quiet and steady flow to the sea. Its gradient, which may be as much as twenty to thirty degrees at the head, becomes less and less until it is nearly horizontal at the river's mouth, as illustrated in Fig. 24.

While we think of this as the ideal course of a river, and it is typical of many of the great rivers of the world such as the Amazon and the Ganges, and of a great number of smaller ones of which the Po in Italy might serve as an example, one constantly finds variations from this type. Thus the Mississippi does not rise in a mountainous country, but in a moderately elevated region of low relief and it has a very uniform gradient to the sea; in other cases where rivers rise in mountains near the sea the lower plains district, corresponding to *b* of Fig. 24, may be very short or wanting. The rivers of the northern Atlantic coast are mostly between these extremes and their courses lie between *a* and *b*; those of the Southern States are more nearly typical, since they rise in the Appalachian Mountains and flow out upon the Atlantic coastal plain.

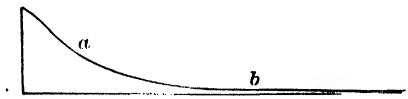


Fig. 24. — Profile of a river showing its gradient.

River Erosion

Corrasion. — If we consider the whole course of a typical river from its source to the sea we find that it performs both destructive and constructive work. The former is a work of erosion and is done chiefly in the upper, steeper part of its course, that portion which is indicated by *a* in Fig. 24; we will examine first the conditions under which this is carried on, while the constructive work will be treated later. In the first place it is clear that, unlike rain wash and gullying, which are a general effect over the whole land area like the result of weathering, the erosion of rivers is local and confined to the bottom and sides of the channels over which the water passes. A river may be compared to a sinuous, flexible and endless file, ever moving forward in one direction, and by means of the moving sand or gravel rasping away the country rock beneath and beside it, thus cutting an ever-deepening trench. This particular phase of a river's work is called *corrasion,* and is one special form of general erosion. The effectiveness with which a river corrades depends on several closely related things; on the tools with which the river has to work, on the amount of them, on the swiftness of its current, and on the nature of the country rock with which it has to deal. These various factors may be examined in detail.

As we have seen, the lowering of the land by decay or wear of its rock surfaces and the removal of the loosened material form what is known as erosion. So far as we are here concerned the loosening is done by weathering and corrasion, and the removal of the débris by running water, which transports it. Rain wash is chiefly transportation of little coherent material, but as the rills flowing together grow into streams corrasion begins, and correspondingly increases. Thus we have *weathering, corrasion,* and *transportation,* as the three phases of general erosion.

The River's Tools. — Clear water moving over rock surfaces erodes but very little. It has a certain solvent power and may thus slowly dissolve and disintegrate rocks, and in this action can be aided by substances carried in solution, especially carbonic acid. In this case the rock which is chiefly attacked is limestone, composed of carbonate of lime, and for reasons which have been previously explained (p. 25). This is, however, a chemical process, rather than mechanical erosion, or corrasion. In order to corrade, a river must have tools, and these are supplied by the sand and silt which it carries, and by the gravel and pebbles it can move if swift enough, either in its regular flow, or in times of flood, see Fig. 25. This material is supplied to the river chiefly by rain wash and by its tributaries, but in regions of soft material the stream may also obtain it directly by wearing and undermining the sides of its channel. If its banks are steep, or even cliff-like, the natural talus which would form at the foot of such a slope is seized by the river and carried away to be used as its tools. It is by the striking, bumping, and grinding action of this material, carried along by the current, that the river is able to cut away the rocks over which it runs and to deepen its channel.

Fig. 25. — River bed full of more or less rounded bowlders showing the tools with which the stream works. Big Creek, Haywood Co., N. C. A. Keith, U. S. Geol. Surv.

In this process the material carried by the river is itself necessarily worn, has its sharp angles removed and becomes rounded or spheroidal, — a form characteristic of the river's tools. Thus, if we find river gravels which consist of hard, well rounded pebbles, we infer the material has been transported a long distance; on the other hand if the gravel is composed of angular bits of rock, and its situation shows that it has been transported, we infer that the distance must have been short.

Amount and Size of Material Carried. — Up to a certain point an increase in the amount of grinding material supplied to a river with a given velocity of current aids in its erosive power. Beyond this point an increase is not effective for the reason that the strength of the current is so consumed in the operation of transporting that the check, given by a tendency to erode, would cause the river to deposit instead. This is further discussed under transportation. Since the eroding power depends on the strength of the blow with which the moving particles strike, it is clear that this in turn depends upon the momentum, that is, upon their mass multiplied by the velocity. Hence for a constant velocity the greater the mass of the particles, that is, the larger and heavier they may be, the more effective agents of erosion they become. Thus in a stream carrying intermingled grains of sand and dust-like particles of clay the sand is the really effective agent.

Swiftness; Law of Erosive Power. — It is quite obvious from the preceding paragraph that other things being equal, the swifter a current is the more rapidly it will erode. For, in a given time, not only will the number of eroding particles passing over a rock surface be increased with a swifter current, but the fact that each particle is moving more rapidly will aid its effectiveness. This may be formulated as a law in definite form as follows: *The erosive power of a current varies as the square of the velocity, with equal size and distribution of particles.* That this is true may be easily proved. If we think of an obstacle in the stream, such for instance as the abutment of a bridge, which is being eroded by the impact of sand grains moving by the current and imagine the velocity to be doubled, then on a given surface, for each moment of time, twice as many sand grains will strike as before and each with a velocity twice as great. The effect will therefore be four times as great. If the velocity is three times as great, three times as many grains will strike, each with a trebled velocity, and the effect will be nine times as great. Therefore the effect varies in this case as the square of the velocity.

While this is true in theory the swifter stream will, however, carry larger particles, which, owing to their momentum, strike with greater force.

The actual erosive power varies between the square and sixth power of the velocity, as may be understood after "velocity and transportation" beyond has been read.

Character of the Country Rock. — It is quite evident that if a stream passes through a region whose underlying rock masses are relatively soft or of little coherence it will erode much more rapidly than in a region of very durable rocks. This of course applies as well to general erosion as to those particular surfaces affected by the moving water of the stream alone. Examples of this, as previously stated, are seen in the rivers of New England and eastern Canada, which, flowing over hard crystalline rocks, are relatively clear compared with those of the Southern Atlantic States and of the Great Plains, which pass through regions of soft material and are turbid with the products of rapid erosion.

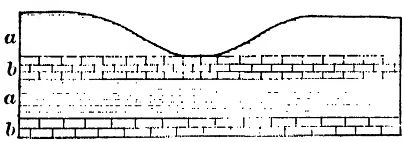


Fig. 26. — Erosion in horizontal beds.

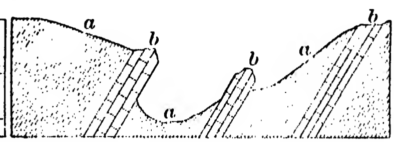


Fig. 27. — Erosion in inclined beds.

The structure of the rock masses has also much to do with the rapidity of erosion. Thus if they are greatly jointed, that is, filled with cracks and fissures, the progress of erosion is greatly aided. If they consist of alternately hard and soft layers, as is often the case, the position of these layers has a great effect in determining the rate of erosion. Thus in Fig. 26 when the hard layer, or bed, *b*, is reached it serves as a floor for the stream and erosion proceeds slowly until it is worn through; in Fig. 27 the stream cuts its way downward along the soft beds, *a*, and the hard ones, *b*, losing their support by undermining, break away in pieces and are worn and carried away. Thus, in this case, the rate is determined by the soft, not by the hard layers. The rock structure shown in the figure could not remain.

Transportation; the River's Burden

A river not only erodes, but also transports and the material carried by it forms its load or burden. While the greater part of this is carried mechanically in suspension, a very considerable portion is transported chemically in solution, while still another part is rolled or moved along the bottom. The ultimate goal of the river is the sea into which, at the end of its journey, its burden is transferred and deposited. The various features of this work demand consideration.

Material in Suspension. — The size of the particles that a river is able to carry in suspension depends on several things; on the

character of a river's current, on its swiftness, and on the relative weight or specific gravity of the particles. With respect to the first of these, if the mass of water forming the current moved forward in a perfectly uniform manner, each particle of water from side to side and from top to bottom moving forward with the same velocity as every other particle, only the very finest material, such as microscopic granules of clay, would remain any length of time in suspension. A sand grain dropped into the stream would sink to the bottom and there remain at rest, unless the stream were strong enough to roll it along. But the current of streams is not of this character. The more central portions are moving more swiftly, sliding over those toward the bottom and sides, while there is a constant interweaving of swifter sub-currents up and down and toward the sides and even backward, forming eddies or whirling movements. The whole effect is like the stirring of water in a glass. Sand at the bottom is quickly lifted and kept in suspension by these movements and thus carried along.

When particles in suspension in pure water attain a certain degree of fineness their settling, even when the water is still, becomes very slow. Thus, as shown by the experiments of Brewer, river waters, such as that of the Mississippi, carrying fine clay particles may remain turbid for many years. In such cases with increasing fineness there seems to be no limit in a practical way between material in suspension and that in solution, however different these may be in theory. If such waters containing clay in suspension be rendered salt and agitated the clay curdles, or coagulates, into lumps, and is quickly deposited, leaving the liquid clear. Thus the clay of river waters, on their attaining and mingling with the salt water of the sea, is deposited on the bottom.

Velocity and Transportation. — The velocity of a current depends, not only on the slope, but also on the quantity of water, thus of two streams having similar gradients and form of channel, the one having the larger amount of water will have the swifter current. It is also well known that the swifter a current is the larger and heavier masses it can transport. Thus it has been found that a current running a fifth of a mile in an hour will carry fine clay; one running half a mile in an hour will transport sand; one of a mile an hour will roll along medium-sized gravel, while one of two miles an hour will sweep along pebbles the size of an egg. Reduced to mathematical form it may be stated that *the moving power of a current varies as the sixth power of the velocity.* This seems extraordinary but may be easily demonstrated. Suppose the problem to be stated as follows: if a current of a given velocity is just able

to move a cube *a*, Fig. 28, what will be the comparative size of the *cube* which a current of twice this velocity can move? Now it has been previously shown that if the velocity of the current is doubled, its striking force is four times as great, because in a given moment of time twice as much water strikes on the cube face of *a* and each particle of water has twice the velocity. The effect of the doubled current being thus four times as great, it could move, striking on the cube face *a*, four such cubes a^1 a^2 a^3 a^4 placed one behind the other to form a four-sided prism. If the current could move one, it could, within limits, move any number of such prisms endwise. But the problem was, how much larger *a cube* could it move? Now it is clear that 16 of these prisms piled together as in Fig. 28 would form

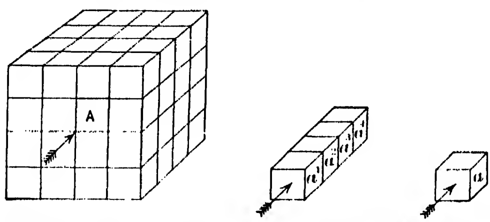


Fig. 28. — Diagram proving that if the velocity is doubled the transporting power is 64 times as great.

a cube and the current striking on the face *A* would just move it. It can be readily seen, however, that the new cube *A* is 64 times as great as the original cube *a*. But 64 equals the sixth power of two. If the velocity of the current were trebled then the striking force would be 9 times as great, for three times as much water would strike in a unit of time with three times the velocity; this would move a prism 9 cubes long and it would require 81 such prisms to be piled together to form a cube. But such a cube would be 729 times as large as the original one and 729 equals the sixth power of three. Therefore the transporting power varies as the sixth power of the velocity. This affects erosion also.

With low velocities of less than a mile an hour and with fine particles this law of increase, although equally applicable, does not seem very striking. Thus sand grains may be a hundred, or a thousand fold, as large as those of fine silts or muds and require a doubled or trebled velocity to move them. But with increasing speeds of miles per hour the effect becomes very marked and this explains why rapid streams of five miles per hour are able to move small bowlders, while sudden floods in narrow valleys, caused by torrential downpours of rain or the bursting of dams, are able to carry with them huge masses of earth and rocks, sweep away bridges and other structures, and cause great damage; see Fig. 29.

It is also clear that the less coherent the material is in which a stream is

eroding the more nearly will the eroding power approach that of its full transporting power; hence the eroding — and transporting — will vary between the square and sixth power of the velocities.

Fig. 29. — In times of flood a stream is able to carry masses and perform work vastly greater than under ordinary conditions, as here shown by the results of flooding. Manti Creek, Utah. H. Gannett, U. S. Geol. Surv.

Effect of Specific Gravity. — The size of the particle that a stream of a given velocity is able to carry depends on the specific gravity of the materials composing the particle. A familiar example of this is seen in that a lead sinker is able to remain at rest on the bottom of a stream which carries away pebbles of an equal size. A practical application of importance is found in the fact that in placer mining, which consists in extracting gold from river sands and gravels, excessively fine particles of the precious metal are mixed with vastly larger ones of the sand and gravel; the water, on account of the high specific gravity of the gold, being unable to transport it. Hence if the gold grains are relatively coarse and angular, that is, unworn, it is inferred that they cannot have been transported far from the original lodes or rocks which contained them and from which they were derived by erosion. The specific gravity of the great mass of material obtained by erosion and carried by rivers

lies between 2.5 and 3.0, that is, it is that much heavier than an equal volume of water. It should also be remembered that a body immersed in water loses weight equal to that of the volume of water displaced, and this greatly aids the transporting power of the stream.

Transport on the River Bed; Traction. — Besides the material carried in suspension a considerable part of the river's burden is pushed, or rolled, along the bottom. What proportion of the whole this may be, cannot be accurately determined; it has been thought that in the case of some rivers it is greater than the amount carried in suspension. From the studies which have been made on the Mississippi it is roughly inferred that of the material which it carries into the Gulf of Mexico about 10 per cent or more consists of coarser detritus moved along the bottom. It is obvious that, other things being equal, the steeper the gradient a river has the larger will be the amount of the moved material.

By observation of experiments in troughs it has been found that of the material urged along the bottoms of streams the amount moved by sliding or rolling of the particles is relatively small, compared with that which progresses by a series of short leaps. For a certain distance above the bottom there is a zone filled with grains moving in this fashion, called *saltation* (jumping), and above this is the material in suspension. In distinction from that carried in *suspension*, the particles urged by rolling, or saltation, are said to be moved by stream *traction*. The amount carried by traction, compared with suspension, varies with a number of factors, such as the swiftness of the current, size of the grains, etc. There is also a collective movement of heaps, or waves, of sand downstream.

Burden Carried in Solution. — All river waters carry in solution salts of various kinds which have been leached from the rocks and soils of the country from which they drain. While, in a measured volume of what we call fresh water, the amount may seem relatively very small, in the aggregate, the weight of material thus dissolved from the land and carried into the sea is enormous. It has been estimated that annually nearly 2,735,000,000 metric tons * of solid substances are thus transported into the oceans. The Mississippi carries about 136,000,000 tons, the Connecticut, a small river, 1,000,000, the Danube over 22,000,000, the Nile nearly 17,000,000. In the Mississippi the amount carried in solution is more than a third as large as that carried in mechanical suspension, the quantities being

340,500,000 tons in suspension;
136,400,000 tons in solution.

* Metric ton = 1000 kilograms = 2204 pounds.

The most important of the substances thus dissolved and transported are the carbonates of lime and magnesia, $CaCO_3$ and $MgCO_3$; the sulphates of lime, soda and potash, $CaSO_4$, Na_2SO_4, and K_2SO_4; chloride of sodium, $NaCl$, and silica, SiO_2. In humid regions where there is much vegetation, the latter by its decay generates carbonic acid, and by the aid of this the percolating waters dissolve lime and other carbonates from the rocks, as previously explained. Hence in humid regions the water of rivers, like the Potomac and the Delaware, has chiefly carbonates in solution; in arid regions where vegetation is sparse or wanting it contains mostly sulphates and chlorides, as in the Colorado and the Rio Grande.

Estimation of a River's Burden. — To ascertain the amount of material carried by a river, its average annual discharge of water must be known, and the average amount of sediment in suspension, and of salts in solution, in a measured volume, obtained. For the former the area of the average cross section and the average flow, in feet per second, must be known, by constantly repeated measurements, during every part of the year. The cross section multiplied by the flow gives the average discharge per second, from which the yearly discharge can be obtained. In a similar manner repeated filtrations of unit volumes of the water will give the sediment in suspension, which can be weighed, while evaporation of the filtrate would yield the salts in solution, which can also be weighed. The composition of the salts can then be found by chemical analysis. The amount moved along the bottom by stream traction can at present be only very roughly estimated, or guessed at.

Many of the great rivers of the world have been more or less studied in this way, the Mississippi probably the most completely, and the following data obtained for this river are of interest and importance:

Average annual discharge 22,000,000,000,000 cubic feet.
Average annual amount in suspension 340,500,000 tons.
Average annual amount in solution 136,400,000 tons.
Average annual amount rolled on bottom, say 40,000,000 tons.
Total annual burden 516,900,000 tons.

Rate of Erosion. — It has been estimated that the above amount of material, in suspension, in solution, and rolled on the bottom, discharged each year into the Gulf of Mexico, on the basis that it averages 165 pounds to the cubic foot, if gathered together would form a right-angled prism with a base one mile square and a height of 250 feet. If we reckon the whole basin of the Mississippi and its tributaries as covering 1,265,000 square miles, and consider

only the material in suspension and solution, it has been calculated from the given data that the basin lowers at the average rate of one foot in 6000 years. An estimate for the whole United States, based on measurements made on its rivers, is about one foot in 9000 years.* These figures appear too great, because the amount moved by stream traction is not included, and the two rivers, the Mississippi and the Colorado, which together transport about 80 per cent of the total material taken from the United States each year and delivered held in suspension into the sea, are also those which must move the most by traction. Older estimates for the Mississippi basin have been as low as one foot in 4000 years, or even less. The rate for its basin must be faster than that of the United States as a whole, because large areas, like the Great Basin, contribute little, or nothing, to the annual run-off.

We cannot therefore at the present time estimate the rate of erosion (denudation) with any approach to real accuracy, but the results are of interest and importance because they indicate the order of magnitude of the figures concerned. We may say, with some confidence, that the area of the United States is being lowered at a rate of one foot in from 5000 to 10,000 years, and probably between 7000 and 9000, and where thousands of feet in thickness of rocks, as we shall see later, have been removed by erosive processes, this gives us some notion of the immensely long periods of time required to do it.

Other rivers, according to circumstances, have given different figures. Thus it has been calculated that the Ganges erodes its basin at the rate of one foot in about 1750 years. But its basin culminates against the loftiest mountains in the world and the river has a proportionately rapid descent and erosive power. The basin is also subject during part of the year to a very heavy rainfall and great floods. Thus the rate is far greater than the average. On the other hand desert regions, like those in central Asia or the Sahara in Africa, with very little rainfall, erode with great slowness, the chief agent of transport being the wind. The average height of North America above the sea has been roughly estimated as about 2000 feet; at the rate of one foot in 7500 years it would take 15,000,000 years to reduce it to sea-level, but as erosive processes (excepting solution) go on more and more slowly as the slope is reduced, this time in reality would be, proportionately, enormously lengthened out.

Manner of Transport. — In considering the manner in which material is carried one must recall that it is only in swift streams and the upper rapid tributaries of great rivers that bowlders and coarse gravels are moved, especially in times of flood. As one goes

* Dole and Stabler.

down a great river the size of the material steadily grows less as the gradient diminishes. This is seen, not only in the matter in suspension, but on the bars and beaches where it is temporarily deposited. Finally, in those rivers which wander through wide plains before they reach the sea, only the finest sands, silts, and clays are discharged into the ocean, and no coarse material is seen, except in those accidental cases where pebbles and bowlders have been carried, attached to masses of river ice or entangled in the roots of trees, which float them downstream.

Nor is the journey a steady or uninterrupted one. The gradient changes from place to place and with it the velocity and transporting power. Material carried down one reach is deposited at the foot of

Fig. 30. — A heavily burdened river. Note the wide bed with many shallow interlacing channels and the very broad, little cut valley. Compare with Fig. 32. North Platte River, above Gering, Neb. N. H. Darton, U. S. Geol. Surv.

it, while at the head of the next, rapid erosion is excavating the channel upward and material is again set in motion. Matter which is dropped at one time of year, when the current is slack, is seized and again hurried forward with the renewed strength that comes in times of flood. Thus, with many waits and pauses, and growing finer by attrition, the mass of material, upon which the river works, is being urged forward, more and more, and ever onward, down stream.

Graded River. — Since in those places where the gradient is lessened a stream tends to deposit (aggrade), while erosion again

sets in when the gradient increases, it follows that, as time goes on, a river proceeds to fill up the hollows and to cut away the projections in its bed and to thus establish a definite gradient. The gradient which the river seeks to establish is that at which, in each part of its course, the velocity is sufficient for the volume of water there present to transport its burden without erosion or deposition; it is then said to be graded. This does not mean that the gradient is necessarily a uniform one from source to sea; it may be relatively much steeper in the upper course, where the burden is of coarse detritus and the water volume small, than in the lower part where the slope is gentle but the water volume large and the load of fine sediment. A very heavily burdened stream, like the Platte, Fig. 30, may become graded on a relatively steep slope, as compared with an underloaded one, which on such a slope would be ungraded and still eroding (degrading). It is also clear from this that the lower parts of rivers, especially of the great rivers, such as the Mississippi, become graded while, in the head waters, cutting and deepening by erosion is still actively going on. See Fig. 32.

Thus in summation we may say that a stream is *at grade, or graded,* when its transporting power and the load given it to carry are equal. It is *aggrading* when the load it has to carry exceeds its ability to transport. It is *degrading* when its ability to do work is in excess of the material to be carried, and the excess of energy is employed in deepening its channel. Grade therefore is a certain balanced condition a river may attain.

River Valleys

River valleys are one of the most expressive features of the work of erosion by rain and running water and their characters are best seen in the upper courses of rivers where these agencies are most actively at work. The normal profile, or cross section of a valley which is undergoing erosion is that of a V, as shown in the diagram, Fig. 31, because the river, occupying a relatively small space, is cutting downward in the center, while at the same time rain wash and gullying tend to broaden the trench which the river makes, by washing down the material composing the valley walls. As already shown, as fast as this débris reaches the river, it is seized and carried away. The profilė which the valley displays de-

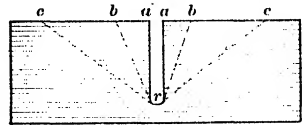


Fig. 31. — Section of a river valley; *ara*, material removed by corrasion; *brb* and *crc*, material removed by weathering and rain wash; river, *r*, trenching downward.

pends then on the relative balance between two agencies, the downcutting by the river and the broadening by weathering and rain wash. Thus in regions where the gradients are very steep, downcutting by the river may proceed much more rapidly than weathering and rain wash, and the valleys will be deeply incised and have profiles approaching *brb* in Fig. 31. As time goes on and the river gradient is lessened the cutting by the river becomes slower and slower; weathering then becomes relatively more and more pronounced and the valley widens out as shown in *crc* of Fig. 31. A valley, of the form shown in Fig. 32, whether or not it is deeply incised below the general upland, but where downcutting by

Fig. 32. — A valley in a youthful stage of its history. Yellowstone River. J. P. Iddings, U. S. Geol. Surv.

the river predominates over weathering and rain wash, so that the valley has steep walls, is called a *young* or *immature* valley; one in which downcutting has become very slow and which is broadly opened by lateral stream cutting and weathering is termed a *mature* valley.

It should be clearly understood, in the use of these terms, *young* and *mature*, that absolute age is not at all referred to; that they are merely expressions to denote relative stages of development of topographic form in a river valley during its history. Furthermore, as discussed in the following section, the form of a valley depends very much on the kinds of rocks encountered by the river, hence in one place the valley may be open and mature, in another narrow with rocky walls and youthful, though the stream may have been running through both places the same length of time. We may therefore apply the terms young, mature, and old to the corresponding stages of development of particular topographic forms, but not to a whole *region*, which may display a variety of topographic features, some of which may be much more advanced than others. Thus we might have a plateau, greatly dissected by an intricate network of streams and their tributaries running in deep, narrow valleys. We may speak of the plateau as mature, or maturely dissected, but the valleys are yet in a youthful stage of development.

Irregularities: Canyons and Gorges. — The irregular windings of most river valleys are due to causes which determine the courses of rivers at the beginning of their history. If, for instance, a river commences upon a new land surface, its course will be determined by the natural slopes and accidents of drainage it may encounter; as time passes and the valley deepens, such windings give rise to the series of alternating spurs which characterize most valleys and are illustrated in Fig. 33. On the other hand it is evident that in the balance between river deepening and the widening of a valley the nature of the material operated upon must be a prominent factor. Few rivers, if any, flow continuously through regions of homogeneous rocks of uniform resistance to erosion. But in the trenching of the river, by its strong grinding action, relative degrees of rock hardness may have but little effect, or none, while such differences may produce marked ones in valley widening which is due to the much milder agencies of weathering and rain wash. A mass of rock of a certain kind may yield readily to the former and resist sturdily the latter. Such variations in material produce local irregularities in the general form of valleys.

Fig. 33. — Course of a river valley with alternating spurs.

This is illustrated in the case of many streams flowing downward from the Rocky Mountains to the plains below. Where they pass through beds of soft, easily eroded shale-rock their valleys are open and smiling; where they enter hard resistant limestone strata the valley walls close into stern and rocky gorges or canyons.

The inability of weathering and rain wash in widening to keep pace with deepening by river trenching in resistant material is well illustrated by the

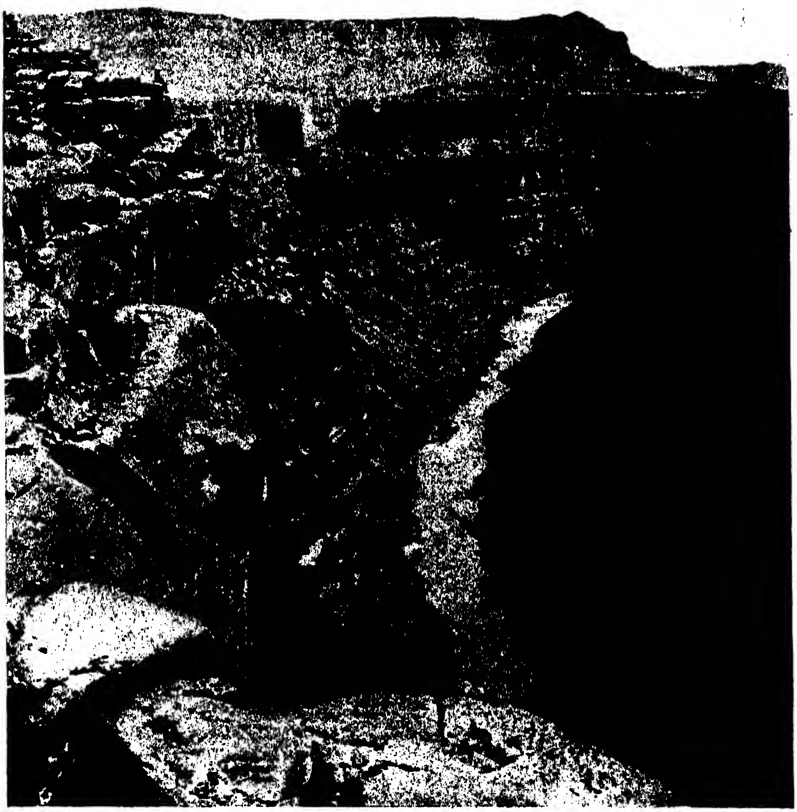


Fig. 34. — Grand Canyon of the Colorado River. View is mostly of the inner gorge; the wall of the upper broader canyon is seen in the distance. J. Hiller, U. S. Geol. Surv.

Ausable Chasm in the Adirondacks, a gorge from 100 to 200 feet deep and from 20 to 40 feet wide, cut in hard sandstone. Still more striking examples are seen in the southern Appalachian Mountains; as in the gorge of the French Broad River in North Carolina, or that of the Tallulah River in

Georgia, which is nearly 1000 feet deep. Notable examples occur in California on the streams flowing from the Sierras and in many other parts of the world.

In arid regions the process of valley widening through weathering is less rapid and effective than in humid ones, while the main drainages, collecting such water as falls, are still subjected to stream trenching. Also, although storms may not be frequent, the rain is apt to fall in heavy downpours, causing strong rushes of water in the drainage channels, with decided erosive effect. Hence deep, narrow ravines, or coulées, gorges, or canyons, are common features of topographic relief in such regions. The nature of the rock masses operated upon is also an important feature in canyon formation, since a narrower valley results in hard resistant rock rather than in a soft, friable one incapable of maintaining steep walls; if the rock beds are horizontal the condition is more favorable than when they are inclined. If the region is much elevated these features become accentuated because of the greater trenching power of the streams, owing to the increased declivity. If the rivers rise in an area of greater rainfall and project themselves into one of aridity these effects become still more marked, owing to the increased and more constant volume of water. All of these conditions of elevation, rock structure, aridity, and water volume are met in the rivers which drain the Plateau region of the Southwest, notably the Colorado River and its tributaries. Rising in the Rocky Mountains, where the precipitation is considerable, they flow out in strong volume into an elevated region of proper rock structure, whose descent affords steep gradients, and whose arid climate renders valley widening extremely slow. Thus we find the Colorado and some of its affluents flowing in the deepest and most magnificent set of canyons in the world. See Fig. 34.

Of all these canyons the Grand Canyon in Arizona is the most stupendous, and one of the most impressive wonders of the world. It is over 200 miles long and from 3000–5000 feet deep and in width it averages about 10 miles. In general its profile shows a broader upper canyon within which lies a

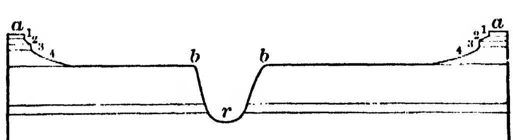


Fig. 35. — Ideal section across the Grand Canyon (after Dutton). *aa*, outer canyon walls; *bb*, inner gorge; 1 and 3, hard resistant beds; 2 and 4, soft beds.

deeper inner gorge, as illustrated in the ideal section shown in Fig. 35. It is cut in horizontal beds of rock of varying degrees of hardness. These rest on underlying granite, which in one stretch has itself been cut into for a depth of 2000 feet in the inner gorge. The harder, more resistant rock layers form cliffs whose talus slopes cover the softer beds. These effects, and the irregular cutting, carving and recessing of the canyon walls through ravines and side valleys, have given rise to enormous and striking architectural forms and appearances, as illustrated in Fig. 34. Some of the masses thus carved out are themselves large mountains. The river is a swift, turbulent stream, turbid and laden with silt, from 200 to 300 feet wide and 2400 feet above sea-level opposite Bright Angel, the place in Arizona where the canyon is attained at present by the railroad, and thus ordinarily seen. The Colorado must be considered as a young river in respect to the character of its valley, and having in view the magnitude of the task which it has yet to accomplish in deepening and widening the valley. In reality it was a rather old river, but it has been rejuvenated, and its period of youth, as well as the work it has to do, has been enormously increased through uprise of the land, a matter which will be considered later.

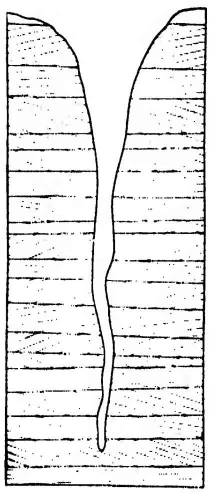


Fig. 36. — Section of the Rio Virgen, after G. K. Gilbert.

A striking instance of the extreme to which canyon cutting may go is seen in Fig. 36, which gives a section on the head waters of the Rio Virgen, one of the tributaries of the Colorado.

Relation to Tributaries. — Examination of drainage systems shows that in a vast majority of cases the tributaries of a river enter it at grade, at the same elevation as the main stream. They are thus said to be *accordant*. The reason for this is, that as the main stream lowers by trenching, the resulting increased declivity which is given the tributaries enables them to keep pace in spite of the smaller volume of water. But this may increase the ratio of the trenching of the lateral valleys over their widening to a greater degree than in the main trunk valley and hence they may be proportionately narrower and steeper. Instances of this are afforded by some of the tributaries of the Colorado River. In their haste to keep accordant relations with the main stream they have cut very narrow canyons whose narrowest profiles are almost like that shown in Fig. 36; Kanab Creek is an example. In some cases, however, in the younger stages of normal valleys, small streams, unable to keep up with a rapidly downcutting river, are obliged to cascade down the main valley walls.

Waterfalls. — One striking feature frequently seen in young val-

leys is waterfalls, the result of the unequal erosion of rock masses which differ in resistance. This is magnificently illustrated in the great cataract at Niagara, which may thus be selected as an example for study. The Niagara River, which drains the four great upper lakes, in its course of 36 miles from Lake Erie runs over a plateau which terminates near Lake Ontario in an escarpment over

Fig. 37. — General view of the Niagara Falls.

300 feet high. The plateau is capped by a hard resistant layer of rock known as the Niagara limestone, under which are soft, easily eroded Niagara shales. Originally the falls was situated at Lewiston at the mouth of the river, and falling over the escarpment had its full height at this point. These relations are seen in Fig. 38. By the gradual disintegration and undermining of the softer underlying shale the harder limestone on top is left projecting as a lip, or table, over which the water falls as shown in Fig. 39. From time to time the projecting table rock, left unsupported and penetrated by joint cracks, also falls and is carried away. By means of this arrangement, and the more rapid wear of the underlying beds, the falls maintains itself and is at the same time steadily moving upstream, leaving a deep gorge behind it, until it is now 7 miles above its original position.

The recession of Niagara Falls and the rate at which it takes place, is a matter of interest and has been the subject of much study because it gives

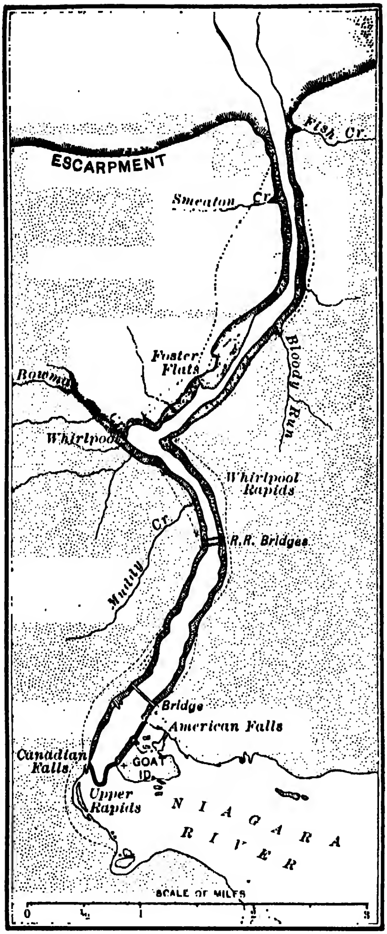


Fig. 38. — Map of Niagara Falls and River, after G. K. Gilbert.

an idea of the length of time involved in geologic processes. It does not seem that at present this rate can be accurately determined. Some hold that the main, or Canadian, fall is receding at a rate of about two feet a year, the American fall at a rate much less than half this; others say more than twice as much. The face of the falls is now comparatively broad, about 4000 feet; when it was contracted in the narrow gorge below, its width was about one quarter of this and, owing to the greater concentrated weight of water, the rate of recession must have been more rapid. If we accept an average rate of five feet per annum, as has been assumed by some, the length of time involved in cutting the gorge (7 miles) would be 7000 years. This is a minimum estimate, but the problem is not so simple as this, since many factors, involving various changes in the river and in the volume of its water which have occurred during the past, must be taken into account, and some estimates which have done this run as high as 70,000 years. Although we do not know the length of time with even an approach to accuracy these estimates are of value in that they show it is to be reckoned in tens of thousands of years, not in hundreds, nor in millions. The height of the falls, which is now about 160 feet, diminishes as they move because the layer of Niagara limestone which conditions them dips gently downward upstream.

Many other famous waterfalls are due to an arrangement of rocks similar to that at Niagara, such as the falls of St. Anthony on the upper Mississippi at Minneapolis, and its tributary streams, which fall into the gorge below; the Shoshone Falls on the Snake River in Idaho; those on the tributaries of the Columbia River, and some smaller falls in New York State like Trenton Falls.

But falls may be produced in other ways as well, by glaciers, as will be noticed later, by the accidental damming of streams by lava flows or landslides, and, as Dana has shown, they are a natural result of the mature erosion of the headwaters of streams in mountain regions whose declivities become steepened by erosive processes.

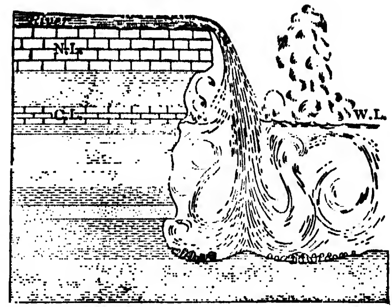


Fig. 39. — Section showing rock layers and cause of falls at Niagara. (After G. K. Gilbert.) N. L., Niagara limestone with soft shale below; C. L., Clinton limestone with shales and sandstones below. 300 ft. = 1 inch. W. L. = water level of pool.

It is clear that waterfalls, whether occasioned like Niagara by unequal hardness of rocks, or due to obstructions in the course of a stream, or to some previous geological action, cannot indefinitely persist; they must be worn away in time and disappear, for reasons previously stated under river grading. The more sediment a river carries, the less likely falls are to be found in its course, or the shorter will be their life. Thus they are commonly regarded as signs of topographic youth in regions where they occur.

Pot-Holes. — A minor feature, seen in the bed of rapid, swirling streams, consists in the presence of pot-holes, Fig. 40. These are circular excavations worn in bed-rock by the whirling action of eddies. If the conformation of the stream bed is such that an eddy persists in one place, the water whirls sand and gravel with it, and this bores downward; although the material wears out in grinding, it is continually replaced by fresh, and the process continues. Such pot-holes may have diameters from a few inches up to 50 feet, and the depth may vary to a similar extent, or be even greater. They are of interest in that they indicate so clearly the action of whirling water and, occurring not infrequently in country rock now far from any stream, they prove that at one time it was the bed of a rapid current.

Constructive Work of Rivers

So far in the study of rivers we have considered the destructive, erosional work which they perform — work done chiefly in their upper reaches and seen in the valleys they excavate in the higher lands. Some rivers have a swift course through elevated tracts of country to the sea, their work is cut short when they enter it, and they deliver their burden at once; but many, and especially the largest rivers of the world, descend into wide lowlands, through which with steady current they wind to their journey's end. In these lowlands, and at the river's mouth, the work done is different from that in the upper reaches; it is largely constructive, rather than de-

structive, and consists mainly in the deposition of the burden assumed through erosion in the higher part of the course.

Fig. 40. — Pot-holes worn in granite rock by stream action. Tuolumne River, Cal. U. S. Geol. Surv.

Flood-Plains. — The lowlands situated on the lower courses of rivers are subject annually to floods caused by spring rains and the melting of snows in the mountains. Unless otherwise checked the river overflows its banks and spreads widely a vast volume of muddy water over these flat lands. The country may appear as a great lake for many miles outward from the course of the river. As the velocity of the water, except in the main channel, is checked in spreading outward it deposits its burden of fine mud and silt. Finally the waters recede leaving the deposit of mud behind. Such a deposit is known as *alluvium* and the flat lands along the lower courses of rivers, built up by these successive deposits, are often called *alluvial plains*. Rivers running through their alluvial plains, like the Mississippi, are generally in that phase of development or stage of their history, which has been previously explained as graded. The condition of the country through which they are passing will be considered later under the heading of baselevel. For convenience in description the whole flood plain may be divided into two parts, the river flats or swamps, and the delta.

River Flats and Swamps. — Examination of the alluvial plains

along the lower courses of rivers shows that in general the land is somewhat higher next to the river and slopes away as one goes from it. The reason of this is, that in times of flood, when the river overflows its banks, the overflowing muddy water, having its velocity checked as it leaves the main current of the river, at once commences to deposit, and the deposits are therefore most abundant near the stream, and composed of the coarsest material carried by it. The low ridges formed in this way are often called *natural levees*. Beyond these the land is low, more or less ill drained, and, in humid regions, commonly covered with trees and other vegetation and thus of the nature of swamps. The river plain of the Mississippi is estimated to cover an area of 30,000 square miles, and a large portion of it consists of extensive swamps.

Fig. 41. — Illustrates bars and deposits made by an aggrading stream in a flat part of its course. Junction of Cooper's River and the Yukon. W. C. Mendenhall, U. S. Geol. Surv.

Although river flats and swamps are most natural and prominent in the lower reaches of streams, they may occur in any part of its course where a sudden lessening of its grade may cause it to deposit extensively, or *aggrade*, see Fig. 41. The stream would here build up a flat, gently inclined area through which it would wind with a steady current; beyond this it would again descend and regain its erosive power. Thus, while such flats are built up at the upper end, they are being carried away by rain and river work at the lower one. Ultimately, as the river becomes graded, they must disappear and hence they are temporary lodgments of material, as contrasted with the final river-plain which must endure as long as the land is affected by the same set of geological conditions. In many cases these upper river

flats represent lakes, or ponds, through which the stream passed and which have been filled up and obliterated by deposit. The same characters and river work, which are features of the great alluvial plains, may be seen in them on a smaller scale.

Deltas: Mode of Formation. — The lower river plain is frequently continued by an area of similar flat, low-lying land extending into the sea or lake into which the stream discharges. This tract usually has a triangular shape with one apex pointing upstream, from which fact it has received the name of delta, since it

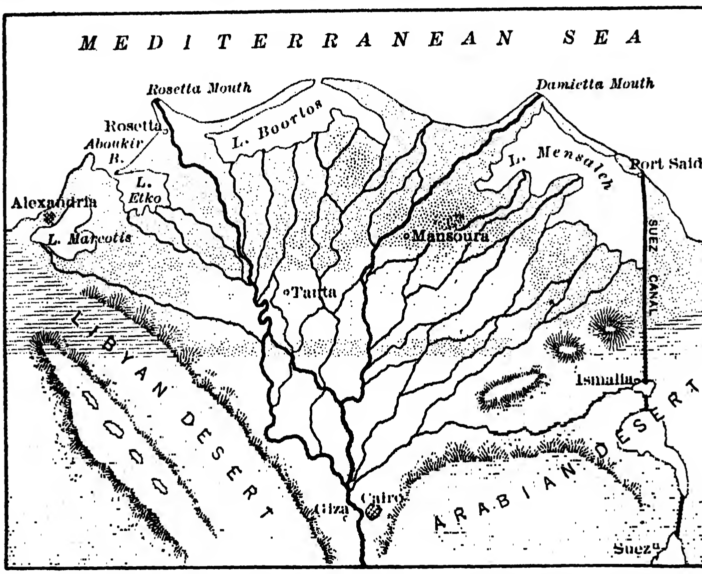


Fig. 42. — Delta of the Nile, showing its form and distributaries.

has a shape similar to the Greek letter so called. On reaching it the river usually splits into many branching streams which wander through the delta in a roughly fan-shaped arrangement as illustrated in Fig. 42. These branches are called *distributaries.* The delta represents land which has been formed by the river and reclaimed from the sea or lake. Although a great part of the burden of sediment carried by the river may be deposited, as we have seen, upon its alluvial plain, another large portion is carried on to the river's mouth. On meeting still water, the current is checked and the sediment in suspension is deposited, while that moved along the bottom comes to rest. Through this continued deposition land is formed, and the growing land pushes seaward. As the current of the river urges forward some distance into the body of water into

which it discharges, deposit takes place along the sides of this current, as well as at the point where it ceases, and this forms seaward a continuation of the natural levees. At the place where the current stops, the heavier material is promptly dropped and this builds up a *bar*, or bars, across the mouth of the river. The rising bars may finally obstruct the course of the river to such an extent that it breaks through the natural levees at some point upstream and seeks an outlet elsewhere, leaving a diminished volume of water escaping by the old channel. The new outlet goes through the same process and thus, by upbuilding natural banks and bars and by breaking through them, the branching system of distributaries is

Fig. 43. — Delta of the Yahtse River, Alaska. I. C. Russell, U. S. Geol. Surv.

formed and shape given to the delta. The branching system extending seaward, as illustrated in Fig. 43, represents the skeleton of the growing delta; between these arms lie very shallow basins which gradually fill up with finer material and thus become land, at first mud flats or swamps, and then more solid land as the annual overflows build it up by their deposits. The result is seen in Fig. 44.

The structure of deltas, as produced by the deposits under different conditions, will be considered in a later chapter.

Conditions Necessary for Deltas: Examples. — Deltas, especially those of great rivers, are commonly formed of very fine muds and silts; as the river descends into its plain, its velocity is diminished, the heavier and coarser material is dropped, the gradient is further lessened by winding, and strength to carry only the finer

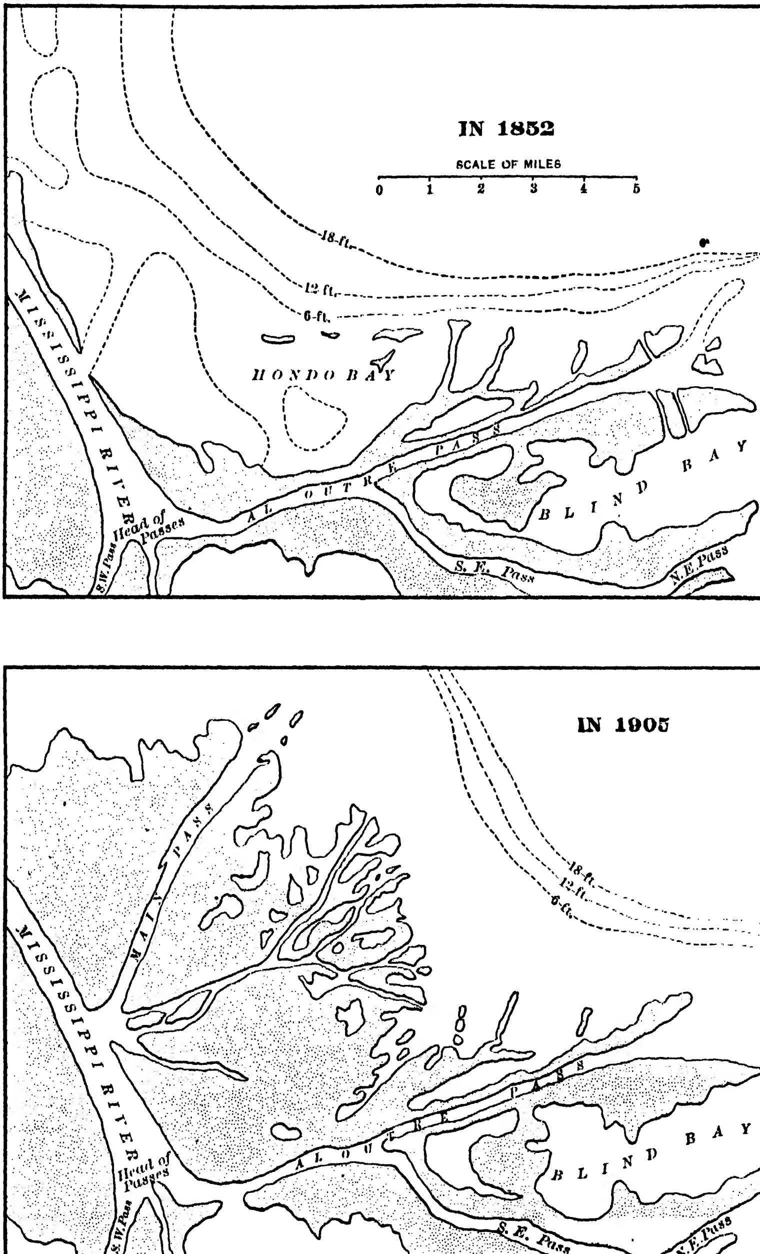


Fig. 44. — Illustrating the growth of the Mississippi delta during 50 years, after G. R. Putnam.

sediments remains. It now becomes a question between the amount and coarseness of sediment which the river can discharge, and the ability of the waves and currents in the body of water into which it enters, owing to their extent and strength, to sweep it away and prevent delta formation. Hence rivers entering lakes and enclosed seas, such as the Gulf of Mexico, the Black, Caspian, and Mediterranean seas, where waves and tidal currents are weak, form deltas. This is illustrated by the Mississippi, the Danube, the Volga and the Nile, all of which have deltas. It may also happen that, even in seas where there is considerable tide and rather strong currents, the conditions may be such, and the volume of sediment so large, that rivers can form deltas. This is illustrated by the Rhine, the Niger, the Ganges and the Hoangho rivers. The Thames on the other hand forms no delta because the strong tidal currents along the English coast sweep the sediments away. On the Atlantic coast of North America there are no deltas because this portion of the continent in a very recent geological period has undergone considerable subsidence, such deltas as the rivers may have previously formed have been submerged, the ocean has entered the river valleys, flooding them and converting them into bays and estuaries, and the rivers are now depositing at the heads of these estuaries seeking to fill them up and form new deltas. If the floor of the ocean is sinking, as appears to be commonly the case under very large deltas, it then becomes a question, between the rate of upbuilding by river deposit and that of the subsidence, whether the river can succeed in maintaining a land area of its delta, or not. It must not be forgotten that in any case a considerable portion of the delta deposit on its seaward slope is under water. This extension consists of the finest material which is carried out some distance before being deposited, and it constitutes the submarine platform on which the landward area rises.

The deltas of great rivers form large areas of land. That of the Nile is nearly 100 miles long and 200 broad on its seaward front; that of the Ganges (and Brahmaputra) 200 miles long and its area possibly 40,000 square miles. The Mississippi delta is 200 miles long, its area over 12,000 square miles, and the thickness of the deposit over 800 feet. The great thickness is due to combined subsidence of the sea-floor and deposit by the river.

The ratio of growth of deltas depends on a variety of circumstances. The Mississippi has been estimated to be pushing forward into the Gulf at a rate of a mile in 16 years. This rate is probably more rapid than in former times for several reasons. The country drained by the river and its tributaries is now widely settled and cultivated, and with occupancy of the land has come extensive destruction of forests and the upturning and exposure of the soil

for agriculture. This produces a more rapid erosion of the basin and a larger volume of sediment. The flood plain is now mostly protected from the annual overflows by a great system of levees, and this has transferred the sediment which would otherwise be deposited upon it to the extension of the delta.

Artificial Levees. — The control and management of large rivers in their flood plains is one of the most serious problems in engineering that civilization has to deal with. Alluvial plains and deltas are composed of fine, rich and fertile soil, and hence are apt to be much cultivated and thickly populated. These lowlands are protected from the annual overflow by levees, as mentioned above, which raise the natural ones above the level of high water. In the Mississippi the increased volume of confined water, by adding to the strength of the current, has increased the scour and deepened the channel. The case of the Po and other rivers long leveed would appear to indicate that this can only be temporary, though, owing to the fineness of sediments, it may long continue. With increased current coarser material must be deposited farther and farther downstream, and the river bed must gradually rise, and, correspondingly, the levees must also be raised. This has been done on the lower Po to such an extent that the river bed and confining levees are stated to be above the tops of the houses in places on the lower plain. The accidental breaking of the levees entails wide flooding of the river plain and great disaster. This has occurred a number of times on the Mississippi, and notably on the Hoangho River in China, entailing in the latter case enormous loss of life.

The obstructions to navigation caused by the bars at the mouths of great rivers have, in the case of the Mississippi, been successfully removed by the building of crib-works, called *jetties*, in such a way as to prolong the natural levees out in shallow water, and to thus continue the current of the stream, so that the load of sediment is deposited in deep water instead of on the shallow submarine top of the delta, while the increased scour deepens the channel.

Alluvial Cones or Fans. — When a swift tributary stream enters into the wider and more level valley of a larger river the sudden change in gradient may cause it to deposit the greater part of its burden on the floor of this valley. In this way semi-cones, or fan-shaped elevations, of deposits are formed. They may be regarded as deltas formed on land, but differ from the true deltas made in water by their shape and, generally, by the coarser material composing them. A view of such an alluvial cone is seen in Fig. 45. They are often conspicuous in the broader valleys in arid districts where material is washed out of the narrower tributary ravines by sudden heavy downpours of rain and deposited. In these regions whole basins may be filled by such rain wash deposits and present very level floors.

Meanders. — A river, either in its upper flats or in its ultimate flood-plain, has a relatively gentle flow owing to the low gradient, and in consequence diminished strength of current. It is therefore

Fig. 45. — Alluvial cone, made by a tributary to a larger stream. Stoughton, Wis. W. C. Alden, U. S. Geol. Surv.

Fig. 46. — Meanders of a stream in a nearly flat region. Trout creek, Yellowstone Park. C. D. Walcott, U. S. Geol. Surv.

easily turned by obstacles, and tends to wander in the plain in a series of winding curves called *meanders*. Nor does it long maintain a set course but shifts about by changing its course and forming new curves. Even if artificially straightened it would soon begin to wander. The reason for this is as follows: The swiftest part of a river current is normally in the middle of the stream; if it encounter any obstacle, such as a rock or stump, it is deflected against the opposite bank. The latter will be eroded, and this will tend to throw the current against the opposite bank (as in *A*, Figs. 47 and 48) which will in its turn be eroded. Thus meanders begin to form

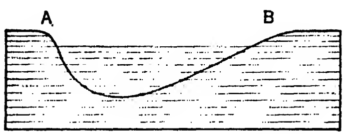


Fig. 47. — Section of a stream channel from *A* to *B* shows it to have the profile seen above, the deepest part lying close in to the bank at *A*. See Fig. 48, *A* and *B* the same.

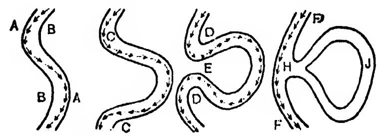


Fig. 48. — Illustrating the formation of meanders and ox-bows.

and a continuation of the process increases them. Meanwhile the current being slackened at *B*, Fig. 48, deposit takes place there and the point grows out as the hollow recedes. Further stages of the process are shown in *C* and *D*. Eventually in the process of meandering, a loop, as at *E*, is cut through, leaving an island in the river, the main current takes the shortest route *FF*, and the entrances to the abandoned channel *HJ* become silted up, leaving a shallow crescentic lake. Such lakes are called ox-bows; they are common along the Mississippi and other rivers on their alluvial plains; they gradually fill up and become sloughs or marshes, and finally perhaps low meadows, though retaining the original form by which their former character may be recognized. Such old abandoned channels are very common on river flats and plains.

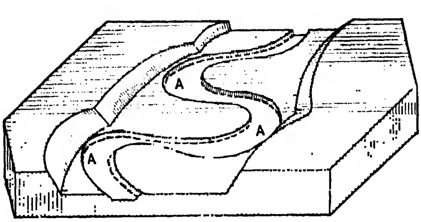


Fig. 49. — A river widening its valley by meandering and planation.

Work on River Plain; Planation. — If a river is graded either temporarily upon an upper flat, or on its plain, it neither lowers its channel by cutting down (corrasion) nor builds it up by deposit (aggrading). In this case, as it wanders by meandering at the same level from side to side

in its valley, it impinges against the valley bluffs from time to time, as at A in Fig. 49, cuts them down by undermining, and carries the material away. By continuation of this process the valley is widened, and this work is known as *lateral planation.*

There appears to be a certain relation between the width of a river and that of the belt within which it can meander. A recent estimate places the width of the latter at 18 times that of the average width of the river. It will be noticed that in meandering a river lessens its gradient, and this is a way in which it seeks to maintain itself at grade. The patterns produced by many rivers, wandering on their alluvial plains, are of wonderful intricacy.

Terraces. — There frequently occur in river valleys long narrow stretches of very flat and nearly level land, often on both sides of the river. Back of them on the side away from the stream may

Fig. 50. — Terraces on the Fraser River, opposite Lillooet, British Columbia. A. M. Bateman, Geol. Surv. of Canada.

rise the ascending slopes of the valley, next to the river they may descend to the present river plain steeply, or even in bold bluffs. Often there are several of them raised one above the other like steps, or shelves. These are known as *terraces;* they are composed of alluvium, of river-deposited sands, gravels, etc., and they are the remnants of former river-plains, when the beds of streams were at their altitude. They are illustrated in Fig. 50. They may be formed in a variety of ways, one of the most important of which is as follows: A stream may at one time in its earlier history be heavily burdened with sediment and deposit this at points of lessened gradient, forming river flats and an ultimate flood-plain.

At a later time, with decreased load and therefore renewed energy, it may begin eroding, cut into these deposits, start a new flood-plain, or flat, at a lower level, and thus leave the remnants of the former plain, or flat, as terraces, as shown in Fig. 51. As the river swings from side to side in this work of planation and removal it is apt to expose resistant masses, such as rock ledges, buried in the old deposits. These may turn the course of the stream, and defend a portion of the former flood-plain from being carried away. They usually mark the situation of projecting headlands in the terrace bluff, which recedes from them on either side, as may be seen in Fig. 49. Changes in the amount of water discharged in different

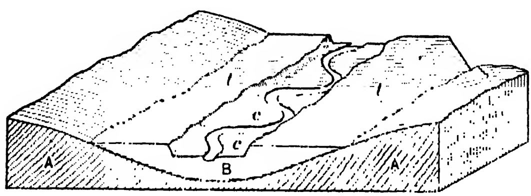


Fig. 51. — Illustrating formation of terraces. *AA*, Section of river-cut valley; *B*, alluvial deposits of river; *tt*, former flood-plain, now forming terraces; *c*, new flood plain.

periods might cause a similar result. On an upper river flat the increased gradient at the lower end, normally working upstream and deepening the channel, may leave remains of the former flat as terraces. Other agencies contributing to their formation will be described later. Owing to their low grades and situations in river valleys they have been extensively used in the location of railway lines.

Structure of River Deposits; Stratification. — Before leaving the constructive geological work done by rivers, it should be stated that all deposits by them, as indeed by all currents of water, whether rivers on the land or tidal currents in the sea, are so laid down, through the sorting activity of water, that they consist of distinct layers, or beds, of varying degrees of fineness. Usually these beds are very regularly parallel for greater or lesser distances, and deposits which exhibit this laminated, banded, or bedded appearance are said to be *stratified*, and the arrangement is called *stratification*. Whether on river flats, on alluvial plains, or in the delta, river deposits are thus stratified. This subject, and the importance of its bearing in understanding the origin of a great class of rocks, will be discussed in detail later, under the structural side of Geology.

Some Phases of River History

Study of the land surfaces of the earth has shown us that they are not permanent geological features. The expression "the everlasting hills" often used in literature has value only in reference to the duration of human life; geologically it has no significance. For not only are the lands subject to change through erosion, as we have seen in the preceding pages, but they suffer changes of level, with reference to the sea, through raising or sinking of the earth's crust. This has often occurred in the past, and to such an extent that sea-bottoms have become land, or land surfaces have sunk to become sea-bottoms. Not only has this happened in the past, but it is occurring now, though so slowly that only one trained in geology is able to perceive it. The land surfaces also have been profoundly modified at times by warpings, by being covered with huge areas of ice, and in other ways. We need not stop to treat these matters here, since we shall study them in detail in appropriate places, except to understand that great changes of land have occurred, and to consider their effect upon the life history of rivers.

Since, therefore, new lands have appeared from time to time, or old ones have had new levels and surfaces given them, it is evident that new drainages have also been initiated. For a long time, such drainages have the characteristics of topographic *youth;* the upper valleys are narrow and V-shaped, the ridges between are wide and often flat; there may be lakes not yet filled up, waterfalls not yet eroded away, and similar features. As time goes on, these are obliterated, the land is everywhere carved into drainage slopes, the main valleys are widened, the hill slopes become gentle and rounded, the rivers meander on their valley floors, they become graded, with harmonious relation between erosion and transportation; in other words they are *mature.* Only, as previously stated on page 51, these are relative terms, not ones of absolute time. We may now consider further stages of river history and land erosion, or, as the latter is sometimes called, degradation.

Baselevel. — If that work of subaerial erosion, performed by weathering and by rain and running water, were to continue unchecked upon a land area, its surface would be gradually lowered, and, in measure as the process continues, the material taken away by the carrying streams is deposited in the sea. But the work of the streams when they reach the ocean is finished; they can do no more eroding, and their burdens must be laid down. The level of the sea therefore is that below which land cannot be eroded by the

agents of subaerial erosion mentioned above. We may therefore conceive of the sea-level as an imaginary surface extended under the land, which represents the limit to which stream erosion and weathering seek to bring downward the land areas. It is the ultimate *baselevel* of erosion by these factors, or, as stated by Davis, "the limit of subaerial erosion is the 'level base' or 'baselevel' drawn through a land mass in promulgation of the normal sea level surface."

If we conceive of erosion continued indefinitely, in its final stage a land area would actually be reduced almost to sea-level, but not quite; it would be nearly flat with a gradient so low that it would be just sufficient to shed the rainfall seaward; erosion and deposition would have therefore ceased; the drainage would have no particular channels and would pass off as from a very flat roof. This is as far as erosion could go; the land would have been very nearly baselevelled, but not entirely so. *Baselevel* then is the imagined plane (extended sea-level) "towards which the land surface constantly approaches in accordance with the laws of degradation, but which it can never reach." (Davis.)

It is evident from what has been said above, and from foregoing pages, that no land has ever been absolutely baselevelled; enough of a slope must remain to carry off the drainage. By sea-level is here meant the normal average level of the sea without regard to the tides, or to those changes which, as we shall see later, have affected the ocean levels in times past. The fact that rivers, like the Mississippi, for example, may erode their channels, as they enter the sea, as much as 250 feet below sea-level, does not invalidate the mathematical conception of baselevel described above. Upper flats and plains, upon which streams meander and through whose extent they are graded, as well as lakes into which they may empty, are often spoken of as *temporary or local baselevels.*

Peneplain. — Since the work of erosion progresses more and more slowly as the heights and gradients decrease, it is evident that the length of time required to bring a land down to a plain almost at sea-level, as described above, would be enormously, almost indefinitely, lengthened out toward the latter end of the process. Long before this could happen the land surface, especially the portion marginal to the sea, would be reduced to a low country of small variation in its general relief. Its elevations would be broad and rolling, with very gentle slopes, and would rise everywhere to the same general height; between them would be wide and very shallow basins, in which the streams would wander more or less sluggishly to the sea, in a well-graded condition. There would be no waterfalls and no lakes. As one gazes over such a landscape

he sees its elevations merge into one level line at the horizon. In addition, whatever may be the nature and structure of the underlying country rocks, whether hard or soft, these features would everywhere persist. A land surface in this stage of wearing down (degradation) by erosion is known as a *peneplain* (almost a plain), see Fig. 54, and its formation is often referred to as *peneplanation*. A peneplain then, is a very old erosional land surface, of low or faint relief, sheeted over with a graded soil cover.

The vast plain of central Russia has been cited as a good example of a modern peneplain; it has been slightly raised and the rivers have been set at work again eroding. Ancient peneplains, which have been uplifted and

Fig. 52. — Drowned river mouth forming an estuary. Balaklava, Crimea, Russia.

then carved by the streams into tracts of hilly country, have been recognized in many places, such as southern New England, Pennsylvania, central Missouri, and the south of England.

It may happen that here and there isolated hills may rise above the general surface of a peneplain, like islands above a sheet of water. They are composed of harder or more resistant rocks or masses so situated at the heading of streams as to be the last residuals, which erosion has not yet been able to reduce to the general level. Such island masses have been called *monadnocks*, after Mt. Monadnock, which rises above the New England peneplain.

It should be noted that topographic forms somewhat similar to peneplains may be made by long continued erosion of the sea or by the work of the ice glaciers, as will appear later; they may appear also in arid regions.

Drowned and Revived Rivers. — If a land surface should be lowered sufficiently by subsidence the lower valleys of rivers would be flooded by the sea and would become estuaries, like Delaware and Chesapeake bays. In this case the river is said to be *drowned.* See Fig. 52. The tributary rivers which formerly ran into the main stream are called *dismembered.* These relations are illustrated in Fig. 53. If a river were carried below baselevel by drowning, it would begin to fill up the estuary by depositing, and this work would go on until the whole bay is filled up and converted into a river-plain, which in a sense may be regarded as its delta. This is the condition of the rivers and estuaries along the Atlantic coast; in which the remaking of the drowned river-plain is only partly completed, as shown in Fig. 53.

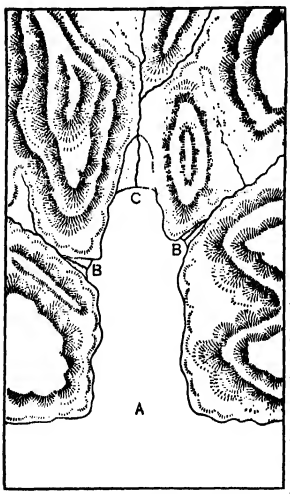


Fig. 53. — Drowned and dismembered rivers. *A*, estuary, drowned river; *B*, dismembered tributaries; *C*, remade alluvial land.

On the other hand, if a land surface should be raised, then the stream and its tributaries, in virtue of the increased gradient, would begin to cut actively and corrade their channels. Features of former mature topography may still be recognized, yet now through the uplift we find the river exhibiting the characters of youth. When this has happened a river is said to be *revived.* Thus the streams of southern New England, which is an upraised former peneplain, have again been set at work and are now excavating their valleys. See Figs. 54 and 55.


Fig. 54. — A revived river. Above, the gentle slopes of the former matured valley; below, the new trench of the revived stream. In the distance the accordant heights of the gently modulated topography show the level of a former peneplain.

Terraces. — In the flood-plains of revived rivers may sometimes be found terraces, similar to those described on page 67, whose mode of formation is of interest and importance in that it involves both depression and elevation

of land and may be described as follows, with reference to the diagrams in Fig. 56.

We first imagine a river *r* to cut out a valley in the underlying rocks *E*, as shown in section in *A*, the land standing at a definite level. If the land is now depressed so that the sea enters the valley, it will be drowned and the river will deposit in the endeavor to raise its bed to baselevel. When this has been done the section will appear as in *B*, the thickness of the deposit *G* indicating the amount of subsidence. If the land is now raised to a new

Fig. 55. — Valley of the Deerfield River, Mass.

level, as in *C*, the gradient is increased and the revived river will again cut down to a new baselevel which we may consider to be at *r*. It will then widen its valley by meandering and lateral planation, as previously described, and while this is going on the remains of the old flood-plain *tt*, usually fronting on the new one below with more or less steep bluffs, will form *terraces*. The height of the bluffs in a general way shows the amount of upraise. Although terraces may be formed in this way, they are more generally produced by other causes, the most important of which has already been described. They are a noticeable feature in the valleys of many New England rivers.

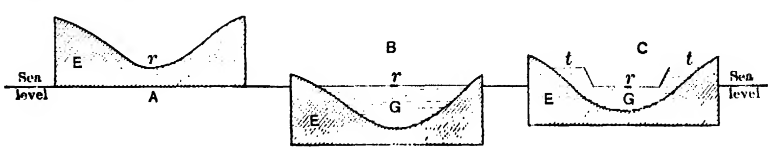


Fig. 56. — Illustrating river-work and formation of terraces. Vertical scale twice the horizontal.

Incised Meandering Valleys. — If we imagine a land reduced to the condition of a peneplain, or nearly so, its streams would wind sluggishly on their way to the sea, meandering over well graded plains at the bottom of wide shallow valleys. If now the land should be raised, the streams would be revived, or, as sometimes said, *rejuvenated*, and as explained in the previous section, set at work again by the increased gradient. They would then sink their

winding courses in their valley floors and thus form new incised meandering valleys, whose depth below the raised upland will depend on the amount of the elevation and the rate at which it took place, compared with the speed at which the streams have been downcutting, and the length of time since they began their work. Such sunken meanders, which a winding stream has incised, are spoken of as being *entrenched.* A view of an incised meandering valley is shown in Fig. 57.

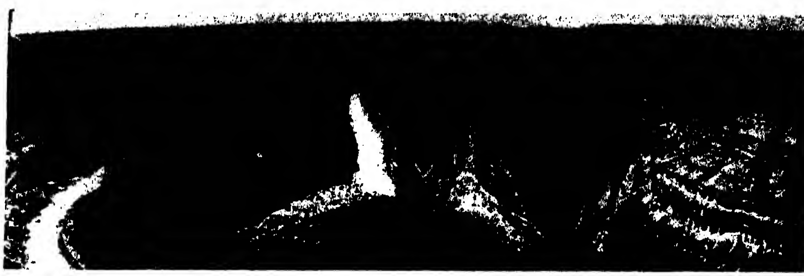


Fig. 57. — Incised meandering valley of the San Juan River, 30 miles below Bluff, Utah; canyon 1200 feet deep. H. E. Gregory, Prof. Paper 93, U. S. Geol. Surv. H. H. Vinson, photo.

The rivers of northern France and Belgium, like the Meuse and the Moselle, furnish typical examples of such valleys. The head waters of the Susquehanna and its tributaries in Pennsylvania also present illustrations of them.

Certain features which these valleys may exhibit are of interest in connection with river work and they may be understood from the diagram Fig. 58, and from what follows. A river, in the circumstances mentioned, is not only cutting downward, it is also cutting in a lateral direction against the concave sides of its curves, as previously explained under meanders, which it therefore tends to enlarge. Moreover, this lateral cutting may be expected to be greatest against those sides of the curves which face up against the general course of the river, since upon them the weight of the current must come with attendant corrasion. These sides of the spurs interlocking between the meanders therefore tend to be "undercut," to present steep and even cliff-like faces to the course of the river, *C, C, C,* Fig. 58. The other, down-valley sides of the spurs, *S, S, S,* on the contrary are apt to descend to the river with more or less gentle and gradual slopes, often covered with sand or gravel deposited by the stream. The reason for the difference is, that since the river cuts laterally against the faces *C, C,* and also vertically downward, these sides of the spurs are being eaten into and consumed, whereas it tends to move away from the sides *S, S,* and with slacker current to leave deposits on them. They are called the *slip-off* slopes, in distinction from the *undercut* ones, *C, C,* since the stream tries to slide away from them without eroding. As one looks down the course of such a valley he sees only the steep and wooded or cliff-like faces of the undercut spurs, which give it

a stern and lonely aspect; when he looks up the valley the cultivated and more or less inhabited fields of the gentle slip-off slopes may confront him.

From what has been said above it will be seen that an entrenched winding river tends to become more circuitous in its course, and that the whole system of meanders moves down the valley. Further, when vertical corrasion ceases and the stream becomes graded, it will begin to build narrow strips of land by deposits *P, P, P,* Fig. 58, along the slacker current sides *S, S, S,* known as *flood-plain scrolls.* In time, as the valley widens by lateral planation (page 66), these scrolls join, and a complete flood-plain is established.

It is evident that as the meanders enlarge and change their curves they may intersect, forming short cuts, as shown in Fig. 48. With entrenched

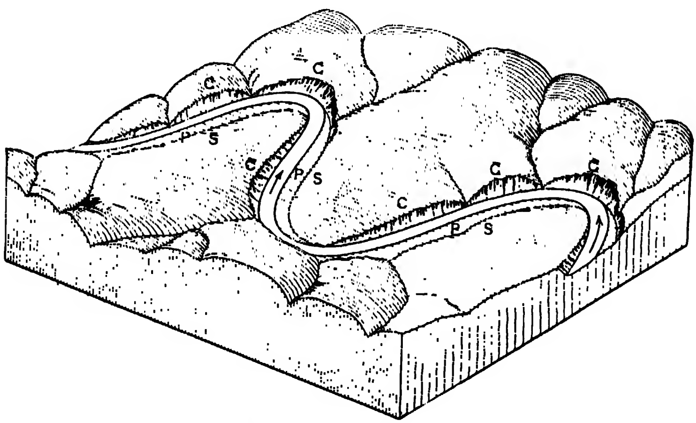


Fig. 58. — An incised meandering valley; arrows point downstream. *C, C, C,* "undercut" slopes of valley; *S, S, S,* slip-off slopes; *P, P, P,* flood-plain scrolls. After W. M. Davis.

meanders it may happen that the neck of land connecting the spur end is actually undercut at the narrowest place, leaving the former spur remnant as an island joined to the mainland by a natural bridge, under which the stream runs in the short cut it has made. Such a bridge modified into an arch by later erosion may be seen in the frontispiece.

Consequent and Subsequent Rivers. — If one imagines for any reason a newly formed land surface, as for instance an upraised sea-bottom, it seems clear that this would have natural bulges and hollows, for a considerable area could not be elevated with a perfectly plane, smooth surface: the courses of this new land would be determined by its natural slopes and topography. Rivers originating in this way are called *consequent* rivers because their courses are consequent upon such original features of the relief of the land. They may persist in a region long after its original topography has been greatly changed by erosive processes having cut away the less resistant areas of rocks more rapidly than the harder, stronger ones.

On the other hand, as time goes on, new drainage channels may appear, not dependent on the original topography, but determined by erosion acting differently on underlying rock areas according to their resistance, structure, etc., as illustrated in Figs. 59 and 60. Rivers formed in this way are called *subsequent*. A consequent river then is one whose course has been directed by the original natural slopes of the land which it drains, whereas a subsequent stream is one occupying a valley which it has excavated by later erosion in harmony with underlying rock structures. Such subsequent streams are apt to be tributaries to more important consequent ones.

In the Appalachian region some of the large rivers, such as the Delaware, Susquehanna and Potomac, are consequent streams. They appear to have originated on an old peneplain which was upraised, and although subsequent erosion, with lowering of the surface, has etched out a whole series of mountain ridges athwart their paths to the sea, they have persisted in their general

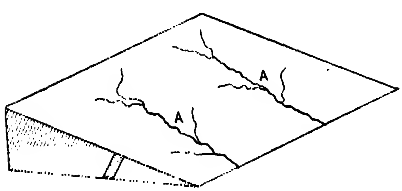


Fig. 59. — Illustrates consequent rivers *AA* on a natural slope, newly exposed; underground structure not yet revealed.

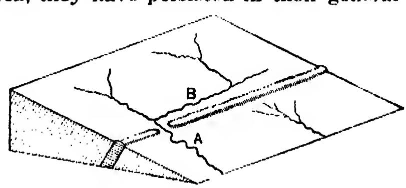


Fig. 60. — With lowering of surface by erosion in Fig. 59, a hard ridge of rock etches out; one consequent river, *A*, persists and becomes a master stream; the other drainage is diverted and forms a subsequent river *B*.

courses, cutting gaps through the ridges, and only here and there being somewhat diverted by these barriers. They have thus become *master streams*, and receive the waters of a great number of subsequent tributaries, whose valleys have been eroded along belts of soft rocks lying between the harder ridges crossed by the master streams. See Fig. 60.

Antecedent Rivers. — During the long life of a river it may happen that an upwarping of the land may take place athwart its course. If the river has a gradient which will give it the requisite energy, and is cutting sufficiently fast, it may be able to saw down its channel through the upwarp in measure as it rises, and thus maintain its course. A stream, whose course has been thus determined by a previous topography and does not now conform to the present relief of the land, is called an *antecedent* river. Thus the Columbia is held to have cut its gorge across the mountains which try to bar its way, and the Great Kanawha River in its course across the upraised plateau in West Virginia has preserved its original winding

course. Similar instances are thought to occur in other parts of the world, as with some of the rivers of the Alps. In each case the river is thought to be older than the elevations; otherwise we could scarcely understand how such drainage ways could occur.

Superimposed Rivers. — It sometimes happens that consequent rivers have had their courses determined by natural features of relief on a new land surface consisting of materials of a certain kind. The courses thus determined may be persisted in by the streams, although, as erosion progresses and they continue to sink their channels, they may be compelled to do so in rocks and rock structures of a very different nature from those at the surface. Finally, erosion may strip off the overlying material entirely, and, with the topography etched out from the underlying rocks, the old stream channels may appear as quite inharmonious. This is illustrated in Fig. 61. A river, whose course has been thus predetermined and which is not now in adjustment with the general topography and rock structures, is called *superimposed.*

In this case its smaller tributaries are mostly subsequent streams. Care should be taken not to confuse antecedent and superimposed rivers. Both

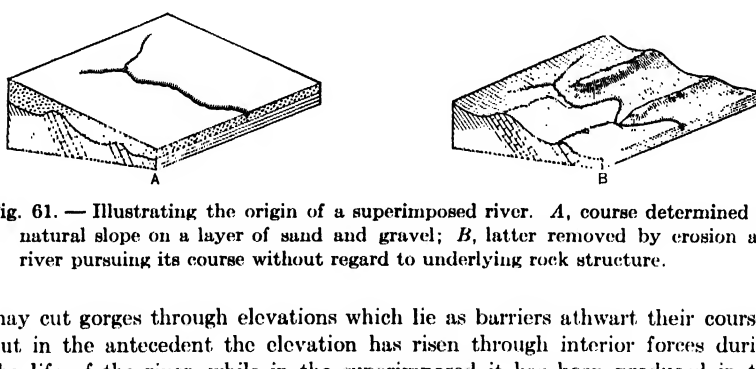


Fig. 61. — Illustrating the origin of a superimposed river. *A*, course determined by natural slope on a layer of sand and gravel; *B*, latter removed by erosion and river pursuing its course without regard to underlying rock structure.

may cut gorges through elevations which lie as barriers athwart their courses, but in the antecedent the elevation has risen through interior forces during the life of the river, while in the superimposed it has been produced in the general lowering of the surface by erosion, through some rock masses being more resistant than others, that is, by differential erosion.

The smoother the underlying rock surface is, the thinner the overlying mantle of material may be to produce this result. If an irregular surface of rocks of varying kinds of hardness and resistance were planed down almost to baselevel and then elevated, the drainage would be rejuvenated and consequent; some master streams would persist in their course, and, although their tributaries through differential erosion would be subsequent (page 76), they would have the characters of superimposed streams, even if a mantle of overlying material may have been practically absent at the time of uplift.

The master streams of the Appalachian region, such as the Delaware, Susquehanna and Potomac, have the characters of superimposed rivers. This is

well illustrated on the Delaware in the fine gorge it has cut through the Kittatinny or Blue Mountains, a barrier which erosion has etched out across its way.

Summary of River Work. — From what has been stated in the preceding pages we see that rivers have a double function; they both erode and transport. The work of erosion is chiefly done in the upper steeper parts of their courses; lower down, on their plains and at their mouths, the work is largely one of deposit and therefore constructional. Their greatest work is the transporting of the material furnished them by general erosion. Finally, we have seen that they have a life history which passes from youth into maturity, and on into old age, and that this life history may be lengthened by rejuvenation. Some features of stream work, such as the nature of their deposits and other ways in which they may modify the relief features of the land, will be treated later.

CHAPTER III

LAKES AND INTERIOR DRAINAGES

Lakes are enclosed bodies of water, either still, or with but a gentle current; they are usually of fresh water, but many lakes, and some very large ones, are saline. Fresh-water lakes have an outlet and in some ways may be considered as expansions of streams. While lakes are found in all parts of the world they are more common in northern and in mountainous regions; the reason for this is explained under glaciers. Lakes are caused by obstructions to drainage, and such obstructions, or lake basins, may be formed in a great variety of ways, some of the more important of which are as follows:

Origin of Lake Basins. — (*a*) Depressions caused either by warping of the earth's crust, or by its breakage and displacement in huge blocks. The first is supposed to be the main cause of Lake Superior, while to the second is due, in part at least, the basins of the large lakes in central Africa. Some smaller lakes in the western United States, such as Abert Lake in Oregon, have been formed by such displacements of the earth's crust. The warping of river valleys may produce lakes, such as Lake Temiskaming in Ontario. Some of the largest lakes in the world belong in this general class.

(*b*) Rock-basins which have been excavated by some means. The most common agency for these is the action of glaciers, as will be explained later; such glacial lakes are found in northern regions, and especially in high mountains; frequently they are inconsiderable in size. Some lakes which fill crater-pits due to volcanic action, like those in central Italy, also belong in this class.

(*c*) Lakes due to natural dams which have been formed across the drainage channels of streams. Such dams may have resulted from various agencies; they may be made by streams of lava, by accumulations of volcanic ashes, or by land-slides, to suggest examples. Most commonly, however, they are made of loose material such as sand and clay deposited by streams, or earth and stones left by the moving ice of glaciers. Thus a swift tributary may deposit more, and coarser, material in a slowly moving main river than the latter

can carry, whereupon a dam will be formed, and the larger stream expanded into a lake above this point, as the Mississippi is changed into Lake Pepin by the dam made by the Chippewa River. Where streams enter the sea through estuaries, the ocean waves may throw up barrier dams across their mouths, converting them into fresh-water lakes. Examples of this are numerous along the Atlantic coast. Perhaps the larger number of lakes, which spangle the surface of the northern part of the country and lend charm to the scenery of New England, the Adirondacks, Minnesota and Canada, are due to dams in valleys left by glaciers. The way in which these dams are made by waves and by glaciers is considered in detail in other places.

Relic Lakes. — Some lakes were once arms of the sea which have been cut off from it by natural dams formed by an upraise of the land, or by material deposited by some agency, such as the delta of a river. Subsequently, the rivers running into them have rinsed the salt out and they have become fresh-water lakes. Lake Champlain is an example of this. Such bodies of water have been recently named *relic lakes,* and their former connection with the ocean is shown by the marine forms of life still living in them, often greatly modified in structure and habits by the changed conditions.

Functions of Lakes. — Several important geological functions are performed by lakes: they regulate the flow of streams with which they are connected, and, by acting as storage reservoirs, prevent disastrous floods; if large, they tend to equalize the temperature of the country surrounding them, cooling the air in summer and warming it in winter. But the most important geological function they perform is in acting as settling basins for the sediment of river waters. In this way great accumulations of transported material are made and river waters are clarified. This is strikingly illustrated in Lake Geneva in Switzerland, into the upper end of which the Rhone pours as a thickly turbid stream, while from the lower end, at the city of Geneva, it issues as a river of beautifully clear blue water. Its deposited sediments have made a delta six to seven miles long at the upper end of the lake.

In lakes, especially the larger ones, may be seen the geological work of waves and of currents along shores. These are best studied, however, in connection with the seacoast, where they are much more strikingly displayed.

The Duration of Lakes. — Considered from the geological standpoint lakes are, in general, only temporary affairs. They are short-lived, since, for reasons previously mentioned, the rivers which maintain them must in time fill them up with sediment, convert them

into river flats or alluvial plains, and thus obliterate them. And also, since the river gradient has a sharper slope where it leaves the lake, the channel must deepen and wear backward upstream faster at this point, and this may cut through the barrier and drain the lake before it is filled. Both filling and draining may coöperate to destroy the lake, but since, in general, water leaving a lake is clear and has little power to erode, filling must be the chief factor. In humid regions, however, as will be shown later, this filling may be done quite as much by deposits of organic life as by transported sediments, or even more.

Yellowstone Lake was once of greater size, and drained south and west into Snake River and the Pacific. The present Yellowstone River, then a much smaller stream, but working rapidly backward on a steep gradient, tapped the lake, partly drained it, and continues to divert its waters into the Missouri and so into the Atlantic.

Lakes, therefore, are considered to be indicative of topographic youth and, in general, this is true. Thus Florida, which is a sea-bottom raised in a recent geological period, still contains many shallow lakes on its very flat, slightly irregular surface, while the other Southern States, which are geologically old and have a mature topography, are destitute of lakes, save those made by the Mississippi and its tributaries in wandering on its flood-plains. The many lakes in the Northern States and in Canada are also the result of a new surface given the land during the recent ice age.

The larger lakes in Florida are probably consequent, due to the flooding of natural shallow basins in the upraised surface, but many, possibly most, of the very great number of small lakes and ponds appear to be subsequent, in that they occupy hollows leached out after the elevation by solution of the underlying limestone.

The lakes of glacial origin in the north may fill depressions, either ground out in the country rock by the moving ice, or left in the irregular surface of the sheet of débris deposited when it melted, or they may be due to the deposits forming dams in valleys, as will be considered later under glaciers.

There are exceptions to this general rule that lakes are short-lived and therefore recent. The great size of some lakes, such as those forming the group of the Great Lakes, often combined with special geological events, as in the case of Great Salt Lake, may serve to prolong the lives of some past the period when we should normally have expected them to disappear.

But although lakes must eventually be obliterated by filling, or draining, or both, there is a considerable difference in their final his-

tory, and also in their nature, dependent on the climate of the region in which they are situated, and this demands consideration.

Lakes in Humid Regions. — In those places where the rainfall exceeds the amount evaporated from the surface of standing water annually, all depressions will fill up and become lakes, provided there is no underground drainage. Such lakes must have an outlet, and will overflow, and therefore through change in the water will remain fresh. And, although normally they must disappear through filling with sediments, as they become shallow, or if they were originally small, the process is greatly hastened by accumulation of black carbonaceous matter called peat, resulting from the decay of various forms of plant life, and through this peat they become converted into marshes, bogs, and swamps as the final stage of destruction. This process, and other details regarding swamps, are described in the chapter devoted to organic agencies.

Fig. 62. — A temporary lake, in a semi-arid region. Wyoming. G. I. Adams, U. S. Geol. Surv.

Lakes in Arid Regions; Inland Drainage. — The amount of rainfall received by any region is dependent on the nature of the prevailing winds and on the topography of the country. In all continents there are areas which receive so little moisture that they are arid, or even desert, in character. Thus in North America the country lying between the Sierras and the Wasatch Range, and mainly in Utah and Nevada, which is known as the Great Basin, has a very light rainfall because the prevailing winds coming from the west and the Pacific have most of their moisture discharged by the mountain ranges of California and Oregon before reaching it. In such regions the evaporation may greatly exceed the rainfall; springs are rare, streams infrequent and of scanty volume in respect

to the size of the valleys which they drain; many depressions in these districts, which in humid climates would form permanent lakes, are dry, or only occasionally filled in times of storms, see Fig. 62.

Surrounding such regions are stretches of country, often mountainous, which receive a greater rainfall and whose streams in part are directed into these arid tracts. On reaching depressions they fill them in part and form lakes whose size is dependent on a nicely balanced adjustment between the amount of water received from the river and that lost by evaporation from the surface of the lake. Should the depression be small the river may fill it and pass on, but,

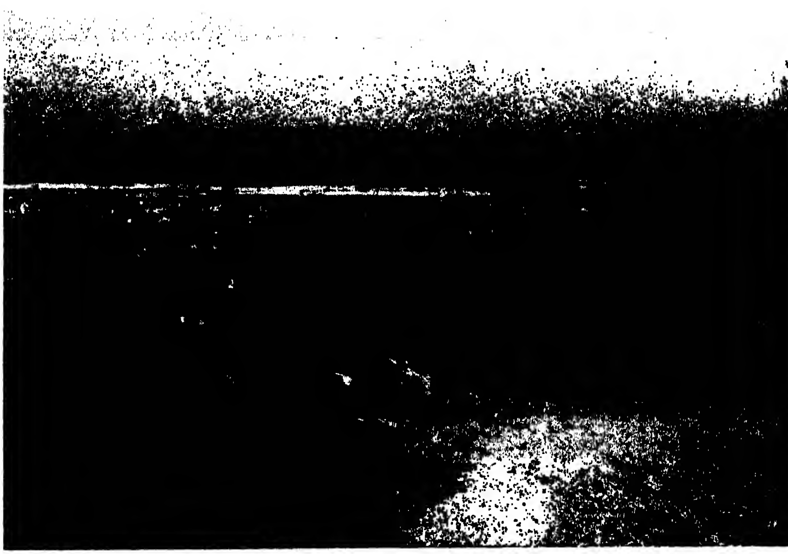


Fig. 63. — Alkaline salt lake near Parma, Colo. C. E. Siebenthal, U. S. Geol. Surv.

as is very frequently the case, the amount evaporated may equal the inflow and the drainage system will then end in the lake. Such lakes vary in size during different parts of the year, or from one period of years to another, in response to fluctuations in the rainfall and in the water discharged into them by the incoming streams. It may also happen that a river running into such a region may dwindle so much from evaporation, before reaching a depression suitable for the formation of a lake, as to entirely disappear. River systems

like these, which end through evaporation in interior basins without reaching the sea, are termed *interior drainages.*

In arid regions the sudden heavy storms which sometimes occur give rise to floods of water, which rushes down through channels to the plains below, where it may spread out in wide thin sheets. Such sheet floods make temporary, extended, shallow lakes, known as playa lakes for the reason that the deposits spread out by the muddy water form monotonously level plains called *playas.*

Salt Lakes. — It has been already explained in the description of the river's burden that a part of it consists of various salts in solution, and that such salts are carried by all streams, even if, in a given volume, the water appears so fresh that they can only be detected by chemical means. In ordinary rivers these salts are discharged into the sea, but in interior drainages, since they cannot be dissipated by evaporation like the water, they must constantly accumulate at the point where the drainage ends.

Fig. 64. — Alkali deposit on the shore of Soda Lake, Parma, Colo. C. E. Siebenthal, U. S. Geol. Surv.

If the river ends by dwindling, its lower part finishes in a stretch covered with salt deposits, sometimes in wet seasons converted into a salt marsh or shallow lake, and known as a *salina.* Examples of these are found in the Tarim River which ends in the Desert of Gobi in central Asia, in the Desaguedero River which carries the drainage from Lake Titicaca in Bolivia, and in many other places. But if the end of the drainage system is a lake the latter is bound in time to become salt through the concentration of these substances, and such salt lakes are features of arid or desert regions in all the

continents. Examples of them are the Dead Sea in Palestine, Lake Van in Armenia and the Aral Sea in Siberia, Lakes Shirwa and Rudolph in Africa, Lakes Eyre and Torrens in Australia, and Lake Chiquita in South America. In North America the best ones are found in the Great Salt Lake in Utah, Pyramid Lake and others in Nevada, and Mono Lake in California.

It is only the final lake in an interior drainage system which becomes salt; an intermediate lake remains fresh because its waters are changed. Thus Utah Lake which flows into Great Salt Lake, Lake Tahoe which runs into Pyramid Lake, and the Sea of Galilee which discharges into the Dead Sea are all fresh, whereas the terminal in each case is salt.

Great Salt Lake has an area of about 2000 square miles; its average depth is about 20 feet. The water is a strong brine, being five or six times as salt as that of the ocean, which in composition it closely resembles; its salinity is about 18 per cent, and the buoyancy, from the increased specific gravity, is so much higher than ordinary fresh water that one floats upon it almost like a cork. The chief salts are common salt (sodium chloride) and sodium sulphate;

Fig. 65. — Islands of calcareous tufa in Pyramid Lake, Nevada. I. C. Russell, U. S. Geol. Surv.

of the former Gilbert estimated the lake to contain 400,000,000 tons, of the latter 30,000,000 tons. Calcium carbonate, which is brought in by the inflowing waters, is deposited as a granular sand on the bottom and shores.

The waters of Great Salt Lake have receded in recent times owing to the

diversion of the Jordan and Bear rivers, which maintain it, for purposes of irrigation, and the consequent evaporation of a part of the supply on land. In the last few years, however, it appears to be again expanding, owing, possibly, to an increase in rainfall and diminished evaporation.

Salt and Alkaline Lakes. — In Great Salt Lake, like many others of its type, chlorides and sulphates are the chief salts, but in some lakes, as in Pyramid Lake in Nevada and its neighbors, there are in addition notable quantities of the carbonates of soda and lime and their waters give an alkaline reaction. We may therefore distinguish between these cases and speak of salt and alkaline lakes, although in western America all natural salts, either as deposits on the land, or in water, are commonly and incorrectly spoken of as "alkali," see Fig. 64. The reason for this difference appears to be that the water of Great Salt Lake drains from an area chiefly occupied by rocks that were once laid down as sediments on the sea floor; on being raised to form land they brought up in their pores the sea salts which are now being leached out, while the Nevada basin is largely covered by igneous rocks, lavas, etc., destitute of sea salts and largely composed of feldspar, whose decay yields carbonates as explained under the formation of soil, page 27. In the alkaline lakes the carbonates, especially lime carbonate, are deposited as calcareous tufa (see page 167) in many striking and curious forms encrusting the enclosing rocks of the basin, in some places in huge masses. See Fig. 65.

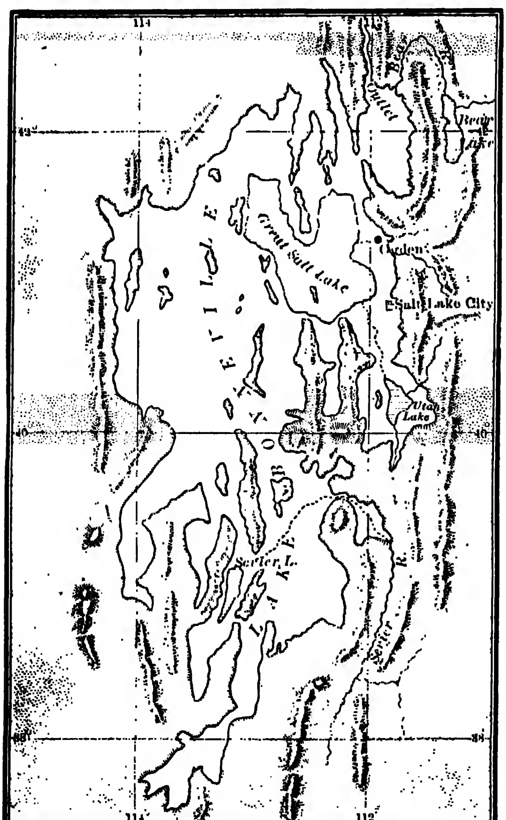


Fig. 66.—Map of the former Lake Bonneville; lined areas show present water-bodies.

Detached Salt Lakes. — In some cases salt lakes are known to have been formed by arms of the sea having been detached from the main ocean by the raising of some intervening barrier, such as sand ridges thrown up by the waves and winds producing them on a small scale, or an upraise of

the earth's crust on a large one. Or they may have been made by dams formed by rivers, glaciers or other agencies. In a humid climate these would become rinsed out and fresh, and thus turned into relic lakes, page 80, but in an arid region they may either dry up and disappear, or become the final evaporating terminus of an inland drainage and thus persist.

The Caspian Sea is one of the best known examples of this. It receives the waters of the Volga and other rivers which are building deltas and slowly filling it. Its water has a composition similar to that of the sea, but is somewhat

Fig. 67. — Former shore lines and wave-cut terraces of the ancient Lake Bonneville.

fresher, because a large gulf on its eastern side with narrow inlet is acting as the final evaporating pan, and in it the salts are being concentrated and deposited. It is therefore being slowly freshened, and is turning into a relic lake. Its former connection with the sea is shown by the chemical similarity of the salts in its waters and by the nature of the animal life it contains, seals, for example, being found in it. It is believed to be the remnant of a great arm of the ocean which once stretched northward, over what are now the steppes of Russia, to the Arctic Ocean.

History of Salt Lakes. — The study of salt lakes and their surroundings reveals the fact that in many cases they are merely the shrunken remnants of much greater bodies of water that once occupied their basins. Thus Great Salt Lake is the remnant of an inland sea as large as Lake Michigan (about 20,000 square miles) and nearly twice as deep, to which the name of *Lake Bonneville* has been given, see Fig. 66, while Pyramid Lake and its neighbors in Nevada are the pools remaining from a great lake nearly as large as

Lake Erie, which has been called *Lake Lahontan.* The evidence for this is found high up on the slopes of the basins where the edge of the old water surface is shown by the line of wave-cut terraces, bars, and beaches, see Fig. 67, such as are described later under the work of the sea, and in the deltas and bars made by the incoming rivers, and now seen lying on the desert floors surrounding the present water bodies, which were the former lake bottoms. The evidence further shows that these lakes were once filled up, and then entirely dried away; were filled a second time and then dried down to their present condition, these variations having been dependent on great climatic changes in these regions. This is also shown by the deposits on their floors; first, salt when the lakes dried up; then clays washed in when they refilled, and which protected the salt from dissolving; and then another layer of salt when they again dried up. This drying of lakes and deposit of salts is of great interest for it enables us to understand the presence of salt beds in the rocks and connect them with dry climates and desert conditions in the past in regions which now have humid climates and a very different character.

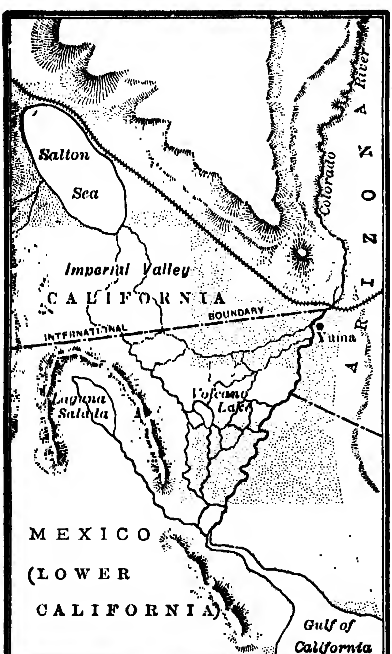


Fig. 68. — Delta of the Colorado River, showing distributary channels, canals and Salton Sea.

In this connection the history of the Salton Sea is instructive. The Gulf of California once extended far beyond its present limits into California. The Colorado River, discharging into this, built its delta as a great dam across the gulf, shutting off its upper portion from the ocean and converting it into a detached salt lake. The river flowed down the south slope of its delta into the gulf; and the lake, thus left without inflow in an arid climate, gradually dried away, leaving a vast desolate salt-encrusted basin, known as Imperial Valley. Recently, in the attempt to divert a portion of the Colorado out on the northward slope of the delta for purposes of irrigation, the river in a period of flood got beyond control and flowed again into the basin,

partly filling it up and forming a lake 450 square miles in area and 80 feet deep, known as the Salton Sea, see Fig. 68. After great expense and labor the river has again been forced back into its seaward channel, and the lake, thus accidentally rejuvenated, will again in time dry up and disappear.

CHAPTER IV

THE OCEAN AND ITS WORK

General Characters. — The ocean covers nearly three quarters of the globe. We are apt to consider its surface as that of a true sphere, everywhere the same distance from the center, and to use this as a datum plane "sea-level," but this is far from being correct. Aside from the fact that the earth is not a true sphere, but a spheroid so flattened at the poles that the polar diameter, on which the earth revolves, is 27 miles less than one in the plane of the equator, the surface is also distorted by the waters being drawn against the continental masses by their gravitational attraction. Thus the sea-level is higher on the coasts than far out at sea, and higher on some coasts than on others where high land-masses, like the Andes, are close to the shore. These vertical differences of level are so small compared with the vast horizontal scale that we cannot detect them by ordinary observation.

The average depth of the sea is about $2\frac{1}{2}$ miles (13,000 feet), varying somewhat in the different oceans. The relief features of the globe naturally divide into two great classes, continental areas

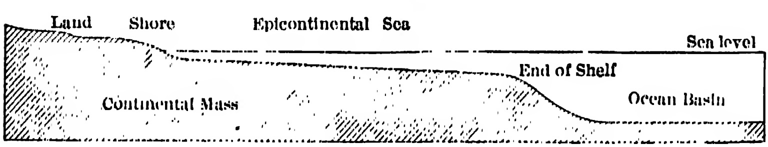


Fig. 69. — Section through edge of continent into ocean basin.

and ocean basins; the amount of ocean water is so great, that not only are the deep basins filled, but also somewhat overflowed, so that a border zone, around most of the coasts of the land areas, is covered out to the depth of about 600 feet. These slightly submerged portions of the continents are known as the *continental shelves* or platforms, and it has been estimated that over 10,000,000 square miles, or 7 per cent of the ocean's bottom, forms their total area. Those parts of the ocean which lie upon them are called *epicontinental seas* (*epi*, upon, or above). See Fig. 69. These relations are of great importance, for, as will appear later, the continental shelves and epicontinental seas have been in the past, as

they are at present, places where processes and results of profound geologic significance occur.

Off the Atlantic coast of North America the continental shelf is broad, about 100 miles, or so, whereas on the Pacific side it is narrow, about 10 miles wide, from Mexico northward to British Columbia, where it begins to broaden. California and Oregon, therefore, slope quite sharply down into the Pacific basin.

The ocean bottom, in general, is monotonously level, and without the smaller relief features, the hills and valleys, of the land. Nevertheless, on a large scale there are swells and depressions rising above, and sinking below, the general floors of the oceans. The depressed areas, when more than 18,000 feet, are known as *deeps*, and there are nearly 60 of them. Some, narrow and trough-like in form, are situated near the margins of the continental platforms; others, irregular or more basin-like in nature, are in the central portions of the ocean. The greatest depth in the Pacific, not far from the Ladrone Islands, is the Challenger or Nero deep, sounded to 5269 fathoms, 31,614 feet; near the coast of Japan is another deep of 28,000 feet. In the Atlantic the greatest deep, of 27,000 feet, is off Porto Rico. These deeps correspond in character with the highest elevations of the land, up to nearly 30,000 feet in the Himalaya Mountains. The earth and the ocean are on such a vast scale, as compared with man, that it is difficult to realize what a mere film, relatively, the sea is upon the surface of the globe. If a ball three feet in diameter were dipped into water, and withdrawn, the film of wetness adhering to it like a skin of varnish would represent the ocean.

It is quite certain that sea-level has changed very often during past ages, not only locally by the relative rise and fall of land areas, but absolutely by increase in the actual volume of water. This point will be considered further in several places, where it is a matter of importance.

Chemical Composition. — The chemical investigations which have been made of sea-water, from various parts of the world and at different depths, show that the composition of the ocean is remarkably uniform. A large part of the known chemical elements have been detected in sea-water, including gold, silver, copper, barium, strontium, rubidium, boron, fluorine, and others, but most of these substances are present in such minute amounts that they have no practical interest or geologic importance. The percentage of salts in sea-water is about 3½, distributed as follows:

100 lbs. of sea-water contain 3.5 lbs. of salts, and 100 lbs. of these salts contain approximately,

	Lbs.
Sodium chloride, $NaCl$	77.8
Magnesium chloride, $MgCl_2$	10.9
Magnesium sulphate, $MgSO_4$	4.7
Calcium sulphate, $CaSO_4$	3.6
Potassium sulphate, K_2SO_4	2.5
Calcium carbonate, $CaCO_3$	0.3
Minor constituents	0.2
Total	100.0

From this it is seen that the chlorides and sulphates of sodium, potassium, calcium, and magnesium are the main substances, with common salt, NaCl, greatly predominating. In addition to these salts, sea-water contains dissolved gases, chiefly air and carbonic acid gas, CO_2, whose amounts vary according to temperature and depth, and accordingly in the past as the ocean has been under glacial or warm climates. Roughly, as an average, we may say that each liter of sea-water contains about 20 cubic centimeters of air, which is much richer in oxygen than the atmosphere, and about 4½ hundredths of a gram of CO_2. The importance of these gases is very great, for upon the supply of oxygen depends the life of the organisms in the sea, while the carbon dioxide, CO_2, whose total quantity is at present about 20 times that in the atmosphere, acts as a regulator of the amount in the air and, since the average temperature over the world depends in part on the carbon dioxide contained in the atmosphere, variations in the quantity in the sea, and therefore in the air, in past times have been, as we shall see later, one factor, in addition to others, productive of great changes in climate and in geological processes.

Functions of the Ocean. — These are somewhat similar to those which have been mentioned as being performed by lakes, but on a vastly greater scale. The ocean acts as a regulator of climate over the world through the great currents moving in it, and especially aids in equalizing the temperature of adjacent land areas; through its waves and tidal currents it is an energetic agent of erosion which destroys the land; it is the final settling reservoir in which are deposited the sediments brought down by the rivers, as well as those produced by its own erosion of the coasts, and lastly it uses this material in a constructive manner in the production of islands and other features peculiar to coast lines. All of these functions are worthy of attention, but since, as will be noted from what is stated above, they so largely depend on the various movements of the waters of the ocean, it is well to consider the latter first. For if the ocean were still, inert, it would have little effect as a factor in geological work, compared with what it now performs. Its movements may be divided into three great classes: *ocean currents, tides* and *tidal currents*, and *waves*.

Ocean Currents. — The unequal heating of the ocean by the sun in tropical and polar regions would establish a slow general circulation of its waters through convective movements. This action, however, is controlled, hastened and magnified by the wind belts of the earth described on page 11, and by the disposition of land and

sea. Driven by the trade winds, there is, in either great ocean, in equatorial regions, a broad current moving westward, along the surface. When this strikes the continental coasts it divides, one part turning northward, the other southward, and each circling returns to the equatorial belt, thus making in each ocean a vast eddy, one north, the other south, of the equator. In the same manner there is a circling movement in the Indian Ocean. These main currents are shown in Fig. 70. In the center is a more quiet area, known in the North Atlantic as the Sargasso Sea. When these broad slow movements, which are known as *drifts*, approach the coast lines, the water by its accumulation and the configuration of the land may become confined and hastened in its motion, giving rise to *streams*. Thus in the North Atlantic the equatorial current striking the north coast of South America is deflected northward.

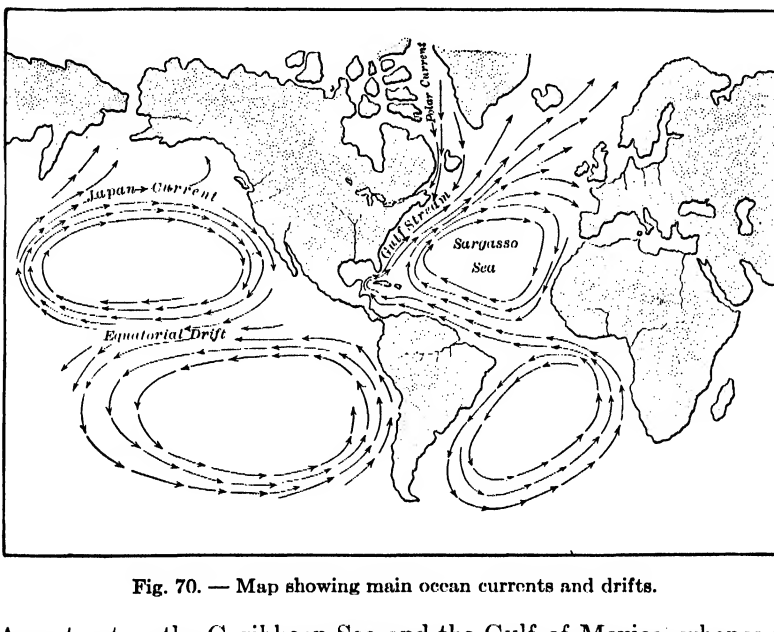


Fig. 70. — Map showing main ocean currents and drifts.

A part enters the Caribbean Sea and the Gulf of Mexico, whence it issues through the greatly confined straits of Florida and passes northeast into the Atlantic as the well-known Gulf Stream. Its velocity as it comes from the straits is nearly 100 miles a day, but this diminishes as it approaches mid-ocean, and as it grows larger and broader. Finally its motion sinks to 10 miles a day and it becomes a general drift of the ocean waters as it approaches the shores of Europe. Here it divides and one part turns southward to pass

along the coast of Africa, and so to join the westward equatorial drift again. Another portion passes northward into the Arctic sea, and to balance this a cold current comes down from the coasts of Greenland around Newfoundland and through the Straits of Belle Isle, past Nova Scotia and New England, and gradually passes under the warm surface current of the Gulf Stream.

In a similar way in the North Pacific a current turns northward and eastward and then turns southward along the western coast of North America. It is known as the Japanese current. These warm currents moving into northern latitudes have a great effect upon climatic conditions in the lands whose shores they strike. The air in the belt of westerlies, page 11, warmed by the water, moves, in its eastward course, inland on the western coasts of Europe and North America, and these coastal regions therefore enjoy a mild and equable climate. But in the same latitude, on the western side of the Atlantic, Labrador and Newfoundland, subjected to air currents which have moved eastward across the continent, have a harsh continental climate, which the cold waters of the returning Polar current help to render almost sub-Arctic. Thus the ocean currents, like the atmosphere, in taking part in the general circulation on the surface of the globe, are great distributors of heat. They carry warmth into the Arctic seas and, returning as cold currents, they bring with them its ice masses to be melted in warmer regions. Were it not for their agency ice would continually accumulate in the Polar regions and, while in general they perform no direct geological work, indirectly, in what they accomplish, they affect geological processes and are, as we shall see later, of great importance. In some places, as in the straits of Florida, they may scour the bottom, but such action is infrequent and of small account compared with the work of the currents next to be considered.

Tides and Tidal Currents. — Without going into elaborate explanation it may be briefly stated that the tide is an uplift, or huge wave, of the ocean caused by the attraction of the moon and, to a lesser degree, of the sun. Were there no continents it would pass around the world in nearly 24 hours, and as there are two such upraises, one on the side of the earth next to the moon, the other on the side opposite, there are two such waves, or tides, each day. In the open ocean, its height is so low and its base so vast, that it is not detectible as a wave in passing under a vessel; but on striking the coasts, as it does every 12 hours, it first piles up upon the shore and then recedes, producing the familiar phenomenon known as the tides. The time interval between tides is 12 hours and 26 minutes, and this interval of 26 minutes explains why the time of high and low water progressively changes each day. The effect of the tide on the coast depends greatly on the configuration of the latter; on projecting headlands its height may be only a few feet, while in

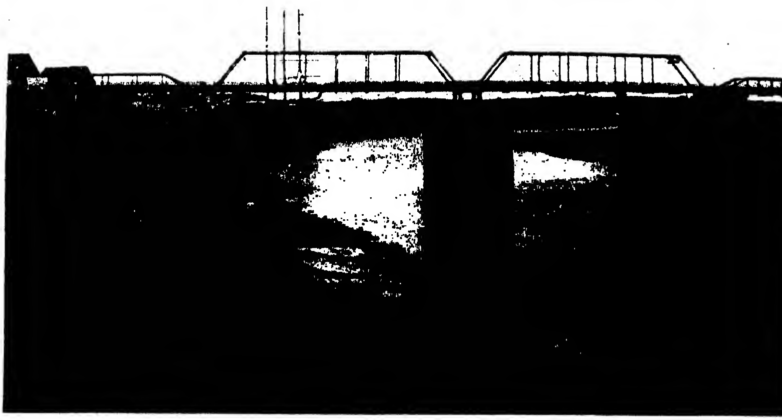


Fig. 71. — Low tide, Port Williams, Nova Scotia, on the Bay of Fundy.

narrow bays and estuaries it may pile the water up to many times this.

The Bay of Fundy on the Atlantic coast affords one of the best examples known of the cumulative effect of the tide in a funnel-shaped estuary. At its head in the Basin of Minas tides of 30 to 40 feet are common, while heights of 50 feet are sometimes reached. The difference between high and low tide at the same place in this basin is strikingly shown in Figs. 71 and 72.

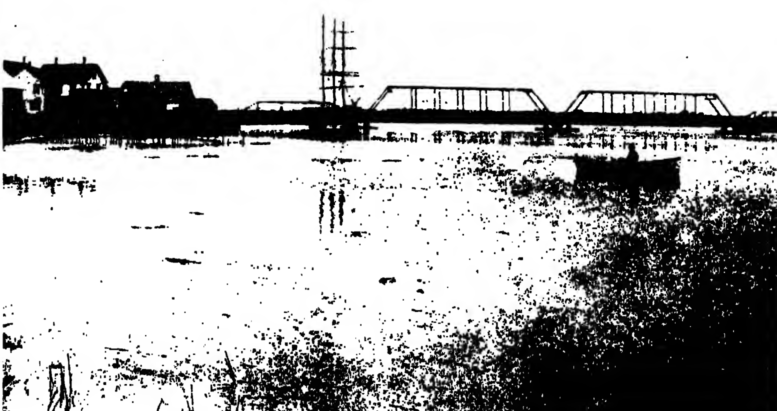


Fig. 72. — High tide, Port Williams on the Bay of Fundy. Same as Fig. 71. A variation of 40 feet.

The immense bodies of water moving in and out of bays and estuaries, and along the coast every six hours, produce strong tidal currents, which, like rivers, have a twofold geologic function in that they both erode and transport. The work done by tides in scour of the bottom and transportation of material along some coasts is very great. Often in entering a long narrow estuary, at the turn from low water, the incoming tide rushes rapidly forward in an immense wave or series of waves 10 to 20 feet in height called a *bore,* or eagre. Examples are seen in the rivers entering the head of the Bay of Fundy, the estuary of the Severn in England, the Seine in France, the Hoogly in India, and the Tsientang in China. See Fig. 73. The erosive power of such currents is very great, while the heavily turbid condition of the water testifies to the amount of sediment transported. Although minute tides may be detected in enclosed seas and large lakes, such as the Black Sea and Lake Michigan, they are too feeble to be of importance, or to perform geological work.

Waves. — These are due to the impulse of the wind. The water particles may be considered as moving in circles which generate the

Fig. 73. — Bore of the Seine advancing upstream.

wave-form; while the form advances the water does not. When waves move into shallowing water, with enlarging circular orbits and decreasing depth, the time arrives when there is not sufficient water to complete the wave-form and, as a result, the top of the wave arching over is unsupported and collapses, the water being given a strong forward motion. This produces the *breakers,* or *surf,* so common a feature along seacoasts. The distance from crest to crest is the *length* of the wave, and that vertically from trough to crest is its *height.* The length of average storm waves in the North Atlantic is 400 feet, the height 20 feet, but in times of great storms the length may be increased to 1000 feet, or more, and the height to over 40 feet. Storm waves with breaking crests are known as

seas, but since waves, which may have a velocity of from 20 to 60 miles an hour, may extend far beyond the storm tract which generated them, they may lose their crests, and in great part their height, and appear as long heavy undulations of the surface known as *ground-swells*. Both ground-swells and seas give rise to breakers or surf, on approaching the coast line.

There appears to be some uncertainty as to how deep the influence of waves on material lying at the bottom extends. It depends on the size of the waves, and is therefore less in lakes and enclosed seas, like the Mediterranean, than in the open ocean. Probably 600 feet represents the limit at which fine sand is disturbed off the Atlantic coast, but at from 60 to 100 feet sand, gravel and even pebbles are moved, a fact of importance in considering the geological work done by the waves.

The water thrown on the shore by the surf returns seaward in a bottom current called the *undertow*. Where waves strike a shore obliquely the run of the water, due to successive impulses, generates a current along shore. While this may be too feeble in itself to transport material, when the latter stirred up by the waves is held in suspension and carried out by the undertow, the *littoral*, or shore current, may move it along. It is by this combined action of waves and currents made by waves and winds that material is moved along the shores of lakes which have no definite, or regular, currents. In the North Atlantic the heavy storms are northeasters and waves coming from this direction strike a blow glancing southward along the coast; to this is attributed the presence of rock débris in the beaches far southward from its place of origin.

The force of waves may be very great. According to Stevenson the force with which the average waves of the North Atlantic strike in summer is about 600 pounds per square foot; in winter over 2000 pounds; in times of severe storms over 6000 pounds. Blocks of rock 10, 20, and 50 tons or even more in weight have been moved by heavy breakers, while large bowlders are tumbled in the surf like pebbles. In this connection it should be recalled that the transporting power of water varies as the sixth power of the velocity, as demonstrated under rivers, page 42. These facts should be borne in mind when erosion by waves is considered later.

Destructive Work of the Ocean: Erosion

Ever restless is the sea; storms arise upon it and the storm waves strike upon the shore; storms pass and subside but the surging ground-swell continues and steadily breaks in surf, beating on the coast. The surface of the ocean, like an ever-moving horizontal saw, is ceaselessly cutting, gnawing, eroding the land. This it does in several ways, producing, according to circumstances, a variety of features which are worthy of consideration.

Wave Erosion. — Sea-water has more or less solvent action on various kinds of rocks, tending to disintegrate them and thus helping the work of the waves. The work of the latter is, however, chiefly mechanical. Most rock masses have crevices or larger cracks in them, and the air or water in these, driven violently in by the impact of the waves, acts as a wedge, disrupting them, and often dislodging large pieces. In this way heavy masonry is often torn asunder. The water, rushing into cavities and suddenly retreating, leaves a partial vacuum which tends to suck away portions of the roof and sides, and the constant repetition of this gives rise to sea-caves, blowing holes, and spouting rocks, so frequently seen on rocky coasts. But the chief eroding action is accomplished by grinding, and in performing this work the waves use as tools the dislodged material, and that which falls from above through atmos-

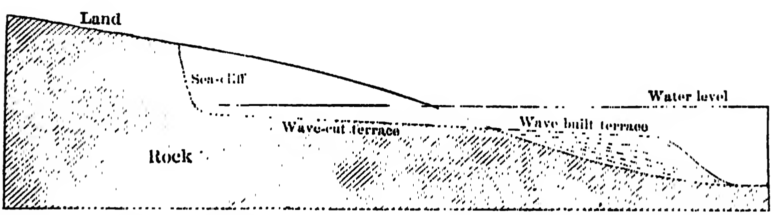


Fig. 74. — Diagram illustrating the production of a sea-cliff, wave-cut terrace and the wave-built terrace.

pheric agencies, and which would naturally form a talus at the foot of the sea-cliff. The constant striking and grinding, not only of sand and gravel, but, as mentioned above, even of heavy bowlders render the waves formidable agents of destruction, through whose work even the hardest rocks are rapidly worn away.

In order to accomplish this task waves must have tools to work with, as stated above. Aside from the mechanically disrupting process, waves of pure water have little eroding power. This is strikingly shown in places on the coast of Norway, where headlands are brought into water too deep to be affected by coastal débris. The rock surfaces, smoothed and furrowed by former action of glacial ice, still retain these characteristic features, though subjected to the constant washing of the waves.

In this process the material used by the waves is itself ground up and consumed — reduced to sand and silt. It loses its angular character and becomes *rounded,* the characteristic form of coastal débris submitted to chafing by the waves, and similar to that of pebbles which have suffered long transport in rapid streams.

For the process of wave erosion to continue, the ground-up ma-

terial must be removed, like sawdust from the track of the saw, in order that fresh rock-surfaces may be exposed to attack, otherwise the fine material would act as a buffer to receive the blows of the waves, and would prevent further erosion. This removal is done by the undertow, which takes the débris back into the sea, and also by tidal and littoral currents, which carry it away. What they do with it we shall presently see. Were it not for the aid of these agencies wave erosion would cease, except where the sea might be invading a continually sinking land surface.

Sea-cliff and Terrace. — The effective erosion of waves is confined to the narrow zone within which they work. The vertical

Fig. 75. — Sea-cliff and terrace extending out below, cut in rock by the waves. Note absence of talus at foot of cliff. Cape Blomidon, Bay of Fundy.

height is of course increased by the lift given to the surface by the tide. This perpendicular distance may be considered the width of the cut made by the horizontal saw, which the surface of the sea forms. Fig. 74 shows this cut made by the waves into the land. As this process goes on, by undermining, and aided by the action of weathering, material is dislodged from above, falls, and is ground up, and thus the sea-edge is terminated by a cliff, where it is advancing inland on higher country. Beneath the surface of the sea at the foot of the cliff lies an area covered with shallow water, or even partly exposed at low tide, which marks the lower limit of wave action. This is called the shore platform, or *wave-cut* terrace. By the action of sand and shingle, swept about by the washing of the waves and the undertow, the terrace is ground away downward and

slowly deepens seaward to the place where the depth prevents such work and the material lies at rest. Here the ground-up material accumulates and this deposit is known as the *wave-built terrace*. These relations are shown in the diagram Fig. 74, and the view in Fig. 75 is of a sea-cliff and a wave-cut terrace in rock at its foot. See also Figs. 76 and 77.

The nature of the sea-cliff depends very much on the character of the material attacked by the waves; thus in hard rocks it may be very steep, per-

Fig. 76. — Irregular coast-line and sea-cliff produced by erosion in nearly vertical rock strata. Pembroke, Wales. Geol. Surv. of England and Wales.

pendicular, or even overhanging; in sand, since the latter would be undergoing constant undermining and sliding down, it may have no steeper angle than that of sand at rest. It also depends on the relative rate of weathering as compared with that of wave cutting; thus clay, which is very tenacious, but easily cut by the waves, may present bold bluffs, though of soft material, whereas granite, which is very hard, and attacked and worn with difficulty, may, through its cracks and joints, be subect to more rapid disintegration by the action of frost (see page 21) and the chemical effect of salt water, and thus present a sea-front of low slope. It is thus not so much the actual hardness of the material as its relative resistance to the two kinds of wear, wave erosion compared to weathering, which determines the nature of the front which the coast presents to the sea. What was said, page 49, regarding the form of river valleys may be considered in this connection. From what has been said it will be readily understood that, unlike cliffs on land which

accumulate a talus below, at the foot of a sea-cliff this may be small or wanting.

Such a bench, or terrace, cut in rock and terminated inland by a cliff, and often with characteristically rounded pebbles and shingle lying upon it or heaped at the foot of the steep, is a decisive sign of surface water-work, either of the sea, or of a lake. And by finding these inland, removed from the present water edge and higher than its level, we are able to recognize that a change of the water-level has taken place; either that the land has been raised, if bordering the sea-shore, or that the water-surface has sunk, if about lakes and inland seas. Thus the terraces about Great Salt Lake, far up on

Fig. 77. — Sea-cliff and stack, the latter a remnant of the former land now eroded away. Coast of Wales. Geol. Surv. of England and Wales.

the slopes of the basin and above the present lake, which are shown in Fig. 67, prove to us that the basin was once filled to this height. This series of benches show the successive levels of the lake formed in the process of its drying up. Many other similar instances of wave-cut terraces, or shorelines, elevated above present water levels, could be mentioned, such as those about the Baltic Sea, which prove elevation of the land. See Fig. 182.

Some geologists, more especially in the past, have believed in the wide extension of shore platforms, and have ascribed large areas of level land, composed of worn-down rocks, to long and vast inroads of the sea and to subsequent uplift; these have been called plains of marine denudation. Later, without denying the possibility of such planing off of the land by the ocean, it was held more probable that where level, or nearly level, regions had been made by the obvious wearing down of former uneven rock surfaces, this had been accomplished by atmospheric erosion, by subaerial peneplanation, as described on page 70.

There is now a tendency to revert to the former idea, and to recognize the existence of marine peneplains, though perhaps not of such wide extent as was formerly believed in, as well as those of subaerial origin. Thus, whether a given peneplain has been made by stream agencies, or by the sea must be determined in each case by the particular set of geologic features which characterize it, some of those which distinguish marine platforms being mentioned above.

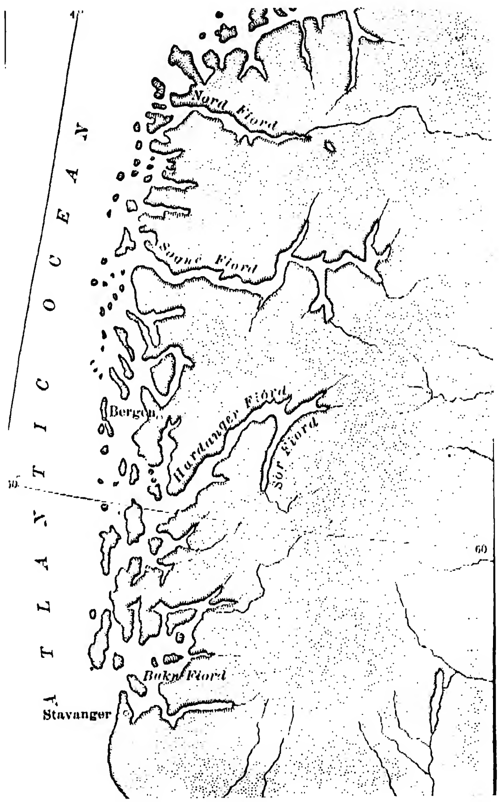


Fig. 78. — Map of a part of the west of Norway, showing the fiords and outer islands of a submerged coast-line.

Irregularities of Coast-line. — The sea, advancing upon the land, finds materials of very different kinds in different places to oppose its progress, and thus upon the nature of the rocks and their disposition the characters of the coast-line, especially with respect to its minor features, very largely depend. See Fig. 76.

Thus if the rocks are composed, as is frequently the case, of parallel concordant layers or beds, called strata, and their edges are exposed to the

waves, the weaker, softer layers are rapidly worn away and the harder beds, left unsupported, break away in blocks. If the beds are horizontal, the harder layers may project for a time as table rocks with cavities under them, as on the coast of Lake Superior. If the beds are vertical, or inclined, but with edges exposed, the hard layers stand out like columns or ribs. If the face of the beds is towards the sea, erosion is slower because the hard layers form an apron, or wall, to protect the soft layers behind them. If the rock masses are homogeneous and hard, like trap or granite, the irregularities are largely determined by the joints, or regular system of cracks in them, and how these are disposed toward the sea front. Finally, if along the coast there are here and there hard masses with softer ones intervening,

Fig. 79. — The Sogne fiord, from Gudvangen, Norway.

the latter are worn away and make coves, while the more resistant masses project as headlands. Thus a bold coast facing the sea is liable to show many minor irregularities of topography.

The sea in its production of an irregular shore-line by dissection of the coast, may cut off portions of land and turn them into islands. Or the portions thus isolated may be bold masses of rock of varied form and appearance, scarcely large enough or far enough from the sea-cliffs to be dignified as islands, which are known as *stacks* or chimney rocks. They are illustrated in Fig. 77 and are common features in various places, as on the coasts of Great Britain.

Indented Coast-lines; Fiords and Estuaries. — The shores of many countries, of which the coasts of eastern North America, of Norway, of Alaska, and of southern Chile may be cited as examples,

present deeply indented outlines; usually there is an outer fringe of islands and behind this are many long bays retreating inland and forming *fiords* into whose heads the rivers empty. This is illustrated in the map of a portion of the coast of Norway, Fig. 78, where these fiords wind back into the country for great distances, 100 miles or even more in some cases, are very narrow and deep, and often bordered by precipitous walls from 1000 to 3000 feet high. A view of one is seen in Fig. 79. Somewhat similar fiords are found in Alaska, Chile, and other places.

It is impossible to believe that coasts with outlines indented deeply on such a scale by embayments having high rocky walls,

Fig. 80. — Former drowned valley forming an estuary, now filled by deposits and changed to a tidal marsh. Cohasset, Mass.

down which cataracts descend from hanging valleys above, as shown in Fig. 79, could have been made solely by the action of the waves, or by the drowning of normal river valleys through submergence. The most satisfactory explanation for them seems to be that in a former time those great streams of ice, called glaciers, filled what were once river valleys and eroded them below sea-level: after this the ice melted and the sea water came in to drown these over-deepened valleys. Fiords, therefore, are glacial troughs, whose lower ends have been flooded and turned into arms of the sea. The manner in which glaciers perform this work will be described in the following chapter.

On the other hand, in distinction from such *fiord shore-lines* there are many deeply indented coasts representing tracts of country with very irregular topography, which, by gradual sinking of the land, have, in part, become lower than sea-level, and whose river valleys

have therefore been submerged, or drowned. Such drowned valleys, formed normally by rivers, are called *estuaries*. Delaware and Chesapeake bays and Long Island Sound are examples of such wide and open valleys which have been submerged. That the estuaries along the Atlantic coast have been made in this way is further proved by the fact that the extensions of the present river channels, or valleys made when the land stood emerged, have been traced by soundings as deep furrows across the continental shelf. The drowning of river valleys by submergence has been previously mentioned on page 72. Indented coasts of this nature are said to have *ria shore-lines,* after the term applied to the northwest coast of Spain, which is cited as the classic example.

The outer fringe of islands, often seen along such coasts, are the tops of hills and more elevated tracts, nearer the former shore, which by submergence have been cut off from the mainland. It should also be remembered that, while the larger features of such shore-lines are due to submergence, subsequent wave work and erosion may have done much to modify them and to give them their present aspect.

Such estuaries are gradually being filled by the streams which empty into them. Their deposits, which may be considered as the equivalents of the stream deltas, are found at the heads of the estuaries forming level stretches of salt-water marshes, or tidal flats, as illustrated in Fig. 80, now flooded by fresh water from the river, now covered by salt water from high tide. The extent to which these tidal marshes have advanced and filled an estuary depends on its size and depth, and on the volume of material furnished by the inflowing streams. See also drowned rivers, page 72. Such estuaries from the in- and outflow of the tide are subject to strong tidal currents, which carry away in part the sediment brought in by the rivers and thus make less rapid the progress of marsh extension at its head. The material thus swept up and down the estuary is often partly deposited in quiet nooks and corners to form tidal flats and marshes and thus helps in such places in estuary filling. It may be added to by that resulting from wave erosion. Another portion is, however, swept out to sea by the out-going tide, and aids in the general constructive work of the waves and currents along the shore.

Constructive Work of the Ocean: Deposition

We have already seen that from a geological point of view a lake must be regarded as a temporary affair; however large it may be, in the vast lapses of geologic time it will become filled up with sediment and obliterated, if its life is not previously cut short by draining. Although, as previously described, an enormous quantity of material is poured into the sea by the rivers from the erosion and waste of the land, and this is aided by the attack of the waves on the coast, the ocean basins are too enormous to be filled by such

means, for if all of the land were reduced to sea-level and the material spread over the ocean floor the average depth would only be reduced about 700 feet. In other words the oceanic level would everywhere be raised less than 700 feet.

But as the material resulting from the wear of the land is mostly deposited in shallow water, in a relatively narrow zone on the continental shelves, by its concentration it becomes a matter of geological importance and, since much of it lies within reach of the action of waves and currents, it is used by them in the construction of new shore features which are of interest to consider. But sediments of this nature, along the shores on the continental shelves, are by no means the only ones occurring on the ocean floor, for even over the bottom of its deep basins, and produced by several agencies, deposits are taking place. We may thus classify under two heads the oceanic sediments, *shallow-water deposits* and *deep-sea deposits.* We will first consider the former.

Beach. — This is the familiar feature which distinguishes the edge of the sea, or lakes. It consists of the material which is being worked over and ground up by the waves. Its upper edge is often marked by a belt of coarser material thrown up and left by the heaviest waves. Lower down it consists of the finer sand and shingle swept in and out and spread by the waves, undertow, and littoral currents. See Fig. 81. Often beaches are inconspicuous or wanting at the foot of steep sea-cliffs and on the contrary are finely displayed at the end of coves and bays, often in curving outline, the reason being that the constant agitation of the waves at the exposed headlands keeps the ground-up material in suspension, and the tidal and littoral currents carry it away along shore until it is deposited in these quieter and more sheltered places. This is especially true in lakes. See page 97. A view of a beach thus formed is shown in Fig. 82.

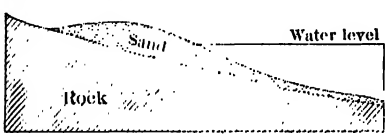


Fig. 81. — Section of a beach, after Gilbert.

It is evident that, as the ocean advances on the land by its erosive work, its edge is marked by the constantly progressing beach. If this should take place on the side of a continental mass which is sinking, the advance of the beach inland becomes more rapid. In a subsiding land area, then, every part is first swept over by a beach line before it becomes the ocean bottom. The consequences of this are marked and of great interest as will be developed later. Beaches have certain marked characters which are described under stratification and by means of them we are able to recog-

nize the fact that what are now land surfaces have been many times submerged beneath the sea and again raised.

The sands spread out on the beach become dry on the retreat of the tide and waves. They are then subject to the action of the atmosphere. Since along coasts the strongest winds are apt to come from the sea, the sand is lifted and dropped inland, forming sand-dunes, as described on page 14. Hence, on low coasts, lines of sand-dunes back of the beach are a very common feature.

Fig. 82. — A curving beach. Conception Bay, Newfoundland. C. D. Walcott, U. S. Geol. Surv.

Barriers. — If the part of the ocean bottom forming the continental shelf slopes out, seaward, very gradually, then the deposits brought down by the rivers and the products of wave erosion, which are spread about on it by the tidal and littoral currents, may be exposed to the action of waves in shallow

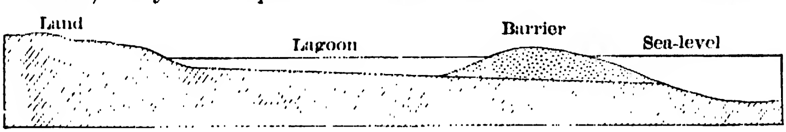


Fig. 83. — Formation of a barrier sand reef.

water at a considerable distance from the edge of the land. When the waves moving landward begin to drag on the bottom, the tops, moving faster, curl over and breakers are formed; the mere wave-form here changes to one of actual onward movement of the water, which rushes forward, tearing up the sand and dragging it along. The undertow sweeps the sand and shingle back, and the material thus put in motion is heaped up at the point off shore where the struggle between the land and sea begins, forming

a long narrow bar, or barrier, parallel to the general trend of the coast, as illustrated in Fig. 83. The waves beating on this may throw up the sand until it rises to the surface; if broad enough the winds may continue the work, lifting the sand into dunes, and thus a long, low, and narrow island fronting the mainland may be developed. Between it and the mainland lies a stretch of shallow water, rarely more than 20 feet deep, called a *lagoon* if small, or a *sound* if large. These are illustrated in Fig. 84.

It is evident that the distance of such a barrier from the mainland will depend on the seaward slope of the bottom. Off the coast of North Carolina, where the bottom shelves out very gradually, they are far out with wide sounds behind them, as seen in Fig. 84; where the shore slopes sharply off into deep water they are wanting, as along the coast of California. In Florida the barrier is close in, forming a long, narrow sound known as Indian River.

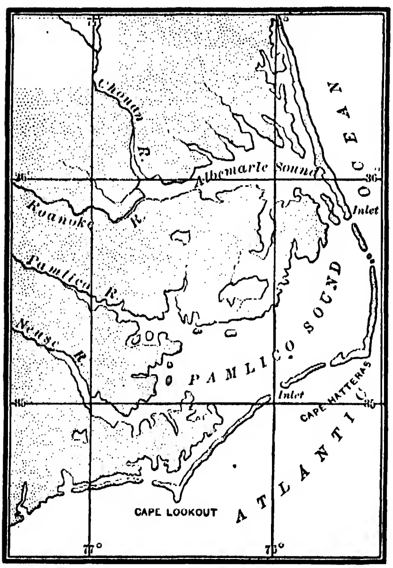


Fig. 84. — Map of North Carolina coast, illustrating the barrier beach and enclosed sounds.

Such a barrier may be built across the mouth of a river, forcing it to flow parallel to the coast for a long distance, or, if the stream is feeble, completely closing the estuary and converting it into a fresh-water lake, Fig. 87, though this is more commonly done by bars, as described in the following section. Ordinarily the sweep of the tide, in and out of such sounds, keeps, by its scour, channel-ways, called *inlets*, open to the ocean.

These bodies of water, being shallow, soon become filled up by the sediments brought into them by the streams, the tide, and by accumulations of animal life, such as shells, etc., and of vegetable matter, such as peat. Thus they may become converted into tidal flats and brackish or salt-water marshes, and these by further growth of vegetation and upbuilding, or by draining through the agency of man, into, eventually, tillable lands. The student will also notice that through the formation of barrier islands a much indented coast-line may be simplified on the ocean front.

Bars and Spits. — We have already seen, page 57, that when a river enters the sea, or a lake, the sediments it deposits form bars at its mouth. This is, however, not the only way in which bars are made, for they are formed especially by waves, and by littoral

and tidal currents as well, and those at the mouths of rivers may be much modified as to their disposition by waves and currents. A current moving along shore may carry sediment in suspension, especially if the water is agitated by storm winds (and this applies particularly to lakes where shore currents are feeble); if it now comes to a narrow indentation of the coast it tends to move across its mouth, rather than to follow its shore, and coming into deeper water it is slowed and the sediment deposited. Thus the current tends to build up an embankment across the indentation and to form a bar. The necessary conditions are that the current should

Fig. 85. — View of a spit. Duck Point, Grand Traverse Bay, Lake Michigan. I. C. Russell, U. S. Geol. Surv.

be fed with sediment from the beach along which it moves, and that it should proceed into deeper water where it slows up and deposits its load. When the current has built the deposit up to the point where the waves may begin work upon it, these may still further heap up the material until it becomes land, and the winds, by raising dunes upon it, may increase its height still more. If the embankment projects out with a free end it is called a *spit*, but if it closes, or nearly closes, the indentation of the coast it is a *bar*. See Figs. 85 and 86. Commonly the scour of tidal currents, rushing in and out of the bay, prevents complete closure and leaves an *inlet;* but closure sometimes occurs, and the enclosed water-body, after it has been rinsed out by the drainage passing into it, becomes a fresh-water lake. Thus by the formation of bars and barriers, or combinations of them, numerous small lakes and ponds along the

coasts have been made. Many excellent examples are found in New England, as illustrated in Fig. 87. Spaces between islands, or between an island and the mainland, are often favorable places for the formation of a bar, and it is common to find islands tied together, or to the mainland, by them, as illustrated in Fig. 86. They occur also in lakes.

Bars may also be formed in shallow seas or on the continental platforms at considerable distances from land by the action of tidal currents. Thus the material brought down by the rivers of southern England and northern France into the British Channel, and that worn from their coasts by wave

Fig. 86. — Island tied to mainland by bar. Bay of Fundy, Nova Scotia.

erosion, is in large part swept by the tidal currents into the North Sea, where the currents meeting the advance of the tide coming into this sea from its northern opening come to rest at high tide, and deposit their load of sediments, forming the numerous shoals and bars which characterize its bottom. The chief features of the relief of the bottom of this sea, however, are probably due to the irregularities of an old land surface, recently depressed below sea-level.

Deep-water Deposits. — The deposits which have been described in the foregoing sections, and which are used by the ocean in its constructive work of making beaches, barriers, bars, and islands, are very largely those occurring in very shallow water close to the land, where the greater part of the land waste is laid down. But in addition to these, as was intimated in a previous section, deposits are laid down in *deep* as well as in shallow water, and indeed one may

say that, of one kind or another, they are formed everywhere on the floor of the sea. Since in several ways they are both important and of interest, they deserve consideration.

Going seaward from the land we may, for practical purposes, divide the ocean bottom into three zones or regions, the continental shelves, the intermediate slopes, and the profound abyss, as illustrated in the diagram, Fig. 88, each distinguished by certain characters as well as, in a general way, by the deposits occurring on them, as follows:

The Continental Shelf. — This has been already described. In general it is limited seaward by the depth of 100 fathoms (600 feet).

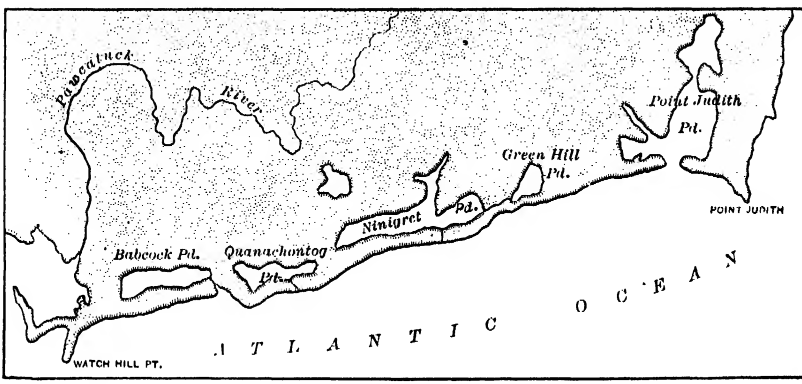


Fig. 87. — Map of coastal fresh-water ponds. Rhode Island.

Taking the whole world into account the area of sea-bottom belonging in this zone is about 10,000,000 square miles. It can be subdivided into the *littoral* or beach region, between high- and low-water marks, and the *shallow-water* area, beyond low-water mark, and therefore never exposed to the air. The littoral zone covers a relatively small space, estimated at about 62,500 square miles for the world.

Epeiric Seas. — The shallow-water area, in addition to the epicontinental seas covering the continental shelves, as previously described, includes basins more or less enclosed by land, which the overflooding of the ocean has filled with salt water. Seas enclosed by land may be divided into two classes, as follows: first, those which are very deep, and through geologic periods, without regard to relative changes of level in land and sea, have maintained themselves as water-bodies; and second, those formed in depressed tracts or down-warps of the continental masses, which have in times

past experienced great changes through variations of sea-level, sometimes being more or less completely emptied of their water, or filled with sediments and turned into land. Examples of the former class are to be seen in the Mediterranean and Caribbean seas, which are very deep; these, however, are not true seas but are known as mediterraneans. Hudson Bay, the Gulf of St. Lawrence, and the Baltic Sea are existing examples of the second class. Such shallow seas as these latter, from their relations to the continents, may be termed epeiric seas (Greek, ἤπειρος, a continent), and those of North America, as we shall see in the second part of this work, have been in the past the theater of important events.

Characters of Shallow Waters. — In the areas of shallow water described, the epicontinental and epeiric seas, the following characters obtain: The waters are more or less agitated to the

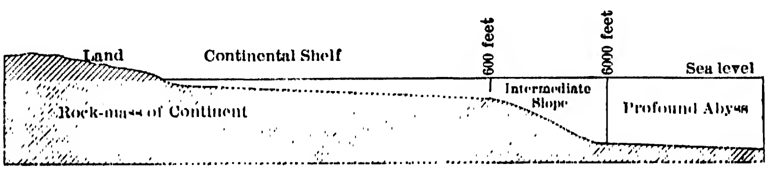


Fig. 88. — Diagram showing different ocean zones.

bottom by wave movements, and are kept in motion by tidal and ocean currents. They are influenced by external temperatures, and thus experience seasonal changes from warmer to colder and the reverse. Over the floor of the continental shelves and inland basins the deposits are chiefly those sediments coming from the land, *terrigenous* (born of the land) as they are called, mainly sands and muds and their intermixtures. In places, where land sediments are scanty, or wanting, as in shallow-water districts about the south coast of Florida, or in the open ocean, the sediments may be wholly produced by organic life, as described later under that agency, and are then mainly composed of carbonate of lime, such as micro-organisms, shells of various kinds, corals, etc.

In this zone, owing to the conditions described and to the fact that light penetrates freely, various forms of life are abundant on the bottom. Vegetation, such as seaweeds (algæ), flourishes and upon it are nourished different kinds of vegetable-eating animal organisms such as certain snail-like shell-fish, herbivorous gastropods, and worms for example, and upon these live carnivorous, or flesh-eating, animals such as certain kinds of fish. A large part of the commercial food-fishes live in this region. The plants and animals of the shelves, owing to the presence of light, exhibit colors, of different tints, which are often remarkably brilliant and varied. There is also in the

sea an immense quantity of minute floating forms of vegetation (algæ), and upon these microscopic plants various animal organisms subsist, to be themselves devoured in turn. This floating life is a great magazine of food.

The abundance of life in the sea varies much between cold and warm waters, and also depends on food supply and oxygen. Of the chief foodstuffs there is usually an ample quantity; the determining factor appears to be the amount of certain substances needed by life in small quantities, which are brought from the land into the sea by rivers. Nitrogen in some form of combination, phosphorus, and silica, are examples of this. It is thus easy to see why life is more abundant around sea-coasts than out in the open ocean. Furthermore, in the shallow coastal and epeiric seas of tropical regions, it has been found that certain bacteria swarm, which have the property of secreting and precipitating lime from sea-water and at the same time of converting the combined nitrogen into nitrogen gas. But, as is well known, warm waters can contain less gas in solution than cold ones; hence the nitrogen tends to escape and the water to absorb a relatively lesser amount of oxygen from the air. Thus in great measure such seas, deprived in considerable part of the necessary staple of life, combined nitrogen, and with lower content of oxygen, are not favorable for the production of life, first, vegetable, and second, animal, which subsists upon vegetable life, in great quantities.

In such seas in temperate or arctic climates, on the other hand, the waters are colder, the denitrifying bacteria do not exist, or are present in small numbers, there is more oxygen in solution, the conditions for life are better, and hence we find their shores and bottoms thickly populated with an abundance of organisms, both animal and vegetable. It is in such waters that the great fisheries of the world are situated. The popular notion that tropical waters must swarm with life because they are warm is quite incorrect, but, on the other hand, it is true that the variety of living forms is far greater in warm waters than in cold ones, and the amount of carbonate of lime deposited by them is much larger.

The deposits as laid down are in concordant layers, or *stratified,* and exhibit certain characters described later in detail under stratification; they may contain in great abundance remains of animals, such as shells, etc., and even of plants, drifted into them from the land. Thus this region and its deposits are of great interest, on account of its forms of life, not only to the zoologist and botanist, but to the geologist as well, since by study of them he is able to perceive that wide stretches of land, now covered with stratified beds of rock and full of organic remains (fossils), were once areas of shallow sea-bottom which have become dry land, and thus exposed, and to understand the conditions under which the bedded rocks were laid down and the animal life flourished, as explained later in this volume.

The Intermediate Slope. — This constitutes that portion of the ocean bottom out beyond the 100 fathom (600 feet) line to a depth of 1000 fathoms (6000 feet). Although the upper border, which is the edge of the continental shelf, is quite well defined, the lower limit is largely one of convenience. It may be considered the wall or side of the true ocean basins, as illustrated in Fig. 88, but it must not be understood that there is always, and everywhere, a marked

change of slope, and a very sharp descent from the edge of the continental shelf to the profound abyss, for, although this is relatively true in a general way, the slope outward is often a gradual one, prolonged for great distances.

In this region, which covers about 18,000,000 square miles of the ocean bottom, the lowest layers of water are not agitated by waves, but only by ocean currents of slow movement. The temperature is, in general, fairly constant and not influenced by seasonal changes of heat and cold. However, when warm and cold currents pass near one another there are at times sudden changes and destruction of life. Light is absent, or only very feeble near the edges of the continental shelf, having been absorbed before penetrating such depths. The deposits are only the very finest of the land sediments which have been drifted out. This is especially the situation of the *blue* and *green muds*. The voyage of the Challenger, an exploring vessel sent out by the British Government, showed that even at distances of from 150 to 200 miles the approach to land could be told by these muds.

The lower limit of the muds is indefinite and often extends far out beyond the 6000 feet line. The blue muds have been estimated to cover 14,000,000 square miles of bottom. In places they are replaced by red muds, as on the east coast of South America, which should not be confounded with red clays found in the abysses, and other areas of the slopes may be in part covered by grey muds composed of volcanic ashes, or by deposits from organic life, as mentioned in the following paragraph:

Owing to the absence of light in this region there is no vegetable life on the bottom, or but a small amount restricted to the zone near the continental shelf. The animal life is mostly confined to certain forms which live upon organic matter in the mud, resulting from decay of the sunken masses of floating microscopic plants and the bodies of free-swimming animals, such as crustaceans, squids, and fishes, which inhabit the top layers of water, and of vegetable matter carried out from land by ocean currents. From the small amount of light, or its absence, the living forms are generally of dull colors, yellows and browns predominating. The green color of these muds is given to them by grains of a green substance called *glauconite*, a silicate of alumina, iron, and potash, which forms in the sea. It is also found in some stratified rocks formed in shallow water, and thus helps to prove that they were former sea-bottom deposits.

The Profound Abyss. — This comprises the whole area of the ocean bottom below the 1000 fathom (6000 feet) mark. In it are also included the lower parts of a few interior basins, such as the

Black Sea and the Roman Mediterranean. The deeps attain a maximum of 31,614 feet. In these profound and monotonous abysses light is absent, there is no movement of the waters except that slow transfer resulting from the unequal heating of the surface of the globe, and the movement of currents on the surface due to the winds, which carries the cold water of the Polar regions into the depths of equatorial basins. The temperature of the bottom layers of sea-water is that at which it has its maximum density, about 34° or 35° Fahr., or very near freezing.

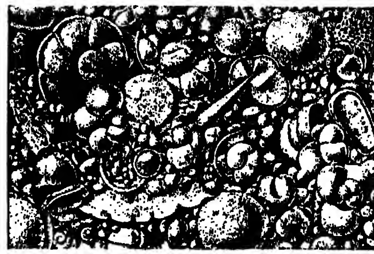


Fig. 89. — Deep-sea calcareous ooze, much magnified, containing shells of Foraminifera. Agassiz and Murray.

Over by far the greater part of the floor of these abysses land-derived sediments are wanting. Over all of them, however, by sounding, peculiar, fine, soft deposits, called *oozes,* have been found, which in different regions have different characters. These are so soft and fine that water movements of one-half mile per day are stated to shift them on the bottom, and it is suggested that the monotonous character of the sea-floor may, in part, be due to the filling of the smaller depressions by these deposits. There are three ways in which these oozes can originate: *a, volcanic,* fine dust from volcanic eruptions carried vast distances by air currents, or volcanic ashes and pumice floating and driven by ocean currents long periods before sinking; *b, cosmic,* the particles of interstellar space which the earth gathers in its journey around the sun; and *c, organic,* resulting from the shells and framework of organisms living in the surface layers of the ocean. Of these oozes the most abundant are a peculiar *red clay,* which covers the floor of the deepest abysses and has been estimated to have an extent of over 50,000,000 square miles, chiefly in the Pacific, and a *calcareous ooze,* resulting from deposition of the shells of minute organisms and estimated to cover nearly as large an area, especially in the Atlantic, Fig. 89.

In the Polar oceans a siliceous ooze occurs, formed from the very ornate shells of diatoms, very minute, simple floating plants whose shell is composed of silica (SiO_2). As the organic oozes do not, in general, occur in the greatest depths, and yet life is nearly everywhere found in the top layers of the oceans, it is inferred that the calcareous shells of the organisms are dissolved before reaching bottom and therefore the oozes they might make are replaced by the

red clay which forms as a final residuum, chiefly from the decay of volcanic and cosmic materials. The presence of the latter is shown by the minute balls, obtained in soundings, which contain metallic iron and have various features similar to the meteorites, or "shooting stars," of larger size which fall on the earth's surface.

The dark cold abysses of the deeper ocean are unfavorable to life, yet it is there. There is no ground vegetation, and the animals living on the bottom must exist upon the sunken bodies of the plant and animal life living in the upper layer of the ocean waters, to which the collective term of *plankton* has been given. The bottom animals are of rather simple types, such as certain worms and star-fishes, some of which are found at great depths; they exhibit a want of color and are often blind. Some have in themselves the means of generating light by phosphorescence.

No formations have yet been generally found among the stratified beds, which now occupy land surfaces, that are exactly comparable to the deposits now found on the floor of the deep ocean basins, and the conclusion has been drawn from this, that the present continental areas have always existed as such, and have never been sunk far enough to become the bottom of the very deep ocean basins, but only of relatively shallow water areas. Some limited occurrences have been found which are held to be of this nature, but in amount these are not more than one per cent of the continents.

Islands. — These may be divided into two classes, according to the positions which they occupy, *continental* and *oceanic*. The former are related to the continental masses, and, in general, they rest upon the continental shelves, and are near the mainland. Long Island on the Atlantic coast is an example. They may be formed in two ways; the first and most important is by the submergence of an irregular coastal land surface, whose higher portions form the islands. Those about the coasts of Maine and Norway, see Fig. 78, are examples. Subsequently the shapes of such islands may be modified by wave erosion. Although generally small, some very large islands, like Newfoundland and Great Britain, belong to this type. Others, like the East Indies, are the fragmented remainders of sunken continents. Still a third way in which continental islands may be made is by the constructive work of waves and currents, and these are illustrated by the low sand islands thrown up as barriers by the waves, such as those along the coast of the southern states.

The true oceanic islands are those rising from the depths of the ocean basins, and are due to accumulations on their bottoms. Such accumulations are chiefly volcanic in origin, although they may be greatly added to by organic deposits made by corals and other animals, as described under organic agencies. Hawaii is an excellent example of a group of oceanic islands composed of lofty piles of volcanic materials rising about 15,000 feet from the bottom of the

deep ocean to a maximum height of nearly 14,000 feet above its surface. Samoa, Bermuda and the Azores are also examples. The Pacific is dotted with many such islands.

In contrast with these, there are many islands, and they include among them some of the largest, like New Zealand, whose situation, at long distances from the continents, would seem to place them in the same oceanic class. But when studied we find that the nature of their rocks and the geological structures which they display, features described in the second part of this work, and other facts lead us to the conclusion that these islands are to be regarded as parts of continental masses, and not as belonging in the deep ocean basins. Also they are surrounded by shallower water which links them to the nearest continental platforms. Thus Spitzbergen is linked to northern Europe, the island of South Georgia to the mainland of South America, and a group consisting of New Guinea, New Caledonia, Fiji, New Zealand, Tasmania, and many smaller islands, appears to be related to the continental mass of which Australia is the largest exposed portion. If we disregarded origin and various geological features, and went merely by geographical situation on the map, many of these might be classed as oceanic islands, but their true relationship is with the continental platforms, not with the deep ocean basins.

CHAPTER V

ICE AS A GEOLOGICAL AGENT

By far the greater part of the land surface of the globe is covered by snow and ice during a part of each year and over vast tracts of it they exist perpetually. Snow and ice therefore are geological factors of great importance whose work is deserving of careful attention and study. The only difference between snow and ice is that the former consists of loose, freely grown crystals of water, whereas in the latter the crystals form a compact mass; they are consequently to be considered together, especially as it is the ice that is the agent of importance.

Ice in the Soil. — The work of frost in splitting rocks, and thus helping in the formation of soil, has been already explained on page 21. The expansion of the water in the soil in freezing also causes movement, and a variety of effects. The vertical motion due to this is the reason why posts and other objects buried in the soil are gradually upheaved and overthrown. On slopes it produces a slow downward *creep* of rocks and soils.

The reason for this creep, which may be explained by the aid of Fig. 90, is as follows: When the soil freezes, a bowlder lying on the slope would be lifted by the expansion in the direction *ab*; on thawing taking place it will sink back vertically in the direction *bc*, thus moving down the slope from *a* to *c*. Thus each year it may be considered to take a step down-hill, and the sum of these steps produces the creep.

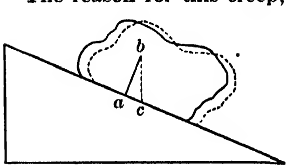


Fig. 90. — Showing downward creep due to frost.

Probably it is due in part to this expansion and movement in forming ice that heavy falls of rock, or slumping and landslides, take place in the springtime in high mountainous regions, especially when aided by the effect of heavy rains. Talus slopes thus tend by creep and sudden sliding to move downward, and where they are extensive may give rise to streams of broken rock material, especially in high mountains, which extend down into valleys. Such rock trains have sometimes been called rock-glaciers, see Fig. 91. What is stated

later in regard to landslides on page 169 may be referred to in this connection.

River Ice. — In streams which freeze, the ice becomes a considerable factor in transporting material, often of considerable weight and size. Along the shore and at the bottom it becomes cemented into stones and gravel on freezing, and along steep bluffs considerable masses of earth and rocks may fall upon it. When the ice breaks up in the spring more or less of this may be carried down-

Fig. 91. — "Rock Glacier" in Silver Basin, Colo. Whitman Cross, U. S. Geol. Surv.

stream attached to the floating ice masses. In narrow places in a river's course the ice cakes may become jammed, forming ice dams, by which the muddy water of the stream is ponded back, overflowing the adjacent lowlands and, as it is thus brought to rest, being made to deposit its load of sediment on the alluvial flats.

Ice in Lakes. — The chief work done by the ice in lakes is accomplished through the thrust which it exerts upon the shore by its expansion. Ice, like other substances, is expanded and contracted by changes of temperature. When a lake freezes, the ice cover first formed accurately fits its surface; if the temperature falls the ice contracts and in so doing cracks, water wells upward into these cracks and is frozen, healing the cracks; the cover of ice again fits the surface of the lake at the reduced temperature. If the latter

now rises the ice must expand, and in doing so exerts an enormous thrust against the shore. By this means loose material is pushed up into ridges, and bowlders lying in shallow water within reach of the ice are crowded ashore, forming walls of stones, or *ice ramparts*, about the border of the lake, as illustrated in Fig. 92.

Fig. 92. — Ice rampart on Lake Tenaya, Calif. G. K. Gilbert, U. S. Geol. Surv.

The Characters of Glaciers

Perpetual Snow-fields. — On all the continents, except Australia, there are places where the annual fall of snow is not entirely dissipated each year by evaporation and melting. In such places snow lies upon the ground all the year, forming perpetual snow-fields. In tropical regions this occurs only on the tops of the loftiest mountains, in temperate regions much lower down, while in polar lands such snow-fields approach sea-level. Thus in passing from the equator to the poles, and depending on average temperature, there is a descending line or surface above which snow lies all the year, and which is therefore known as the *snow-line*.

At the equator this line is from 15,000-18,000 feet high, in Mexico 14,000 feet, in Colorado 12,000-13,000, in the Yellowstone Park about 10,000-11,000, in northern Montana about 9000, in southern Alaska about 5000, in southern Greenland about 2000. In the Alps it is about 9000, in Norway about 5000. The snow-line also depends very much upon the annual precipitation; where this is great it may be much lower than in places with a corresponding latitude where the snowfall is light. Thus at the western end of the Caucasus Mountains on the Black Sea it is 2000 feet lower than on the eastern end of this range near the Caspian Sea, where the climate is much drier. In Bolivia under the equator it is 18,500 feet on the dry western side of the Andes,

16,000 on the moister east side. It is considerably higher in Montana, with a rather dry climate, than in Switzerland in the same latitude with a moister one. In very dry regions snow may disappear more rapidly by evaporation than by actual melting.

Névé; Change into Ice. — In the high mountain valleys, slopes, and amphitheatres above snow-line, which form the gathering ground, or catchment basins, for the perpetual snow-fields, through the weight of the accumulating annual layers the snow becomes *compacted,* and, as it does so, it changes in character. From the loose feathery condition of newly fallen snow, it assumes a granular

Fig. 93. — The gathering ground of the snows. Névé fields in the Mont Blanc region of the Alps.

texture like rather coarse sand, and resembles the granular snow which we are accustomed to see in the spring as the remains of large drifts from the winter. This is largely the result of alternate thawing and freezing at the surface. The great snow-fields composed of this granular snow are called *névé slopes,* or fields.

Since the study of glaciers, and of the various phenomena associated with them, was first undertaken in the Alps, the different names adopted for them are largely the ones used by the French- and German-speaking mountaineers. *Névé* is the French term, *firn* the German one.

Beneath the surface the névé rapidly becomes more compact and passes into porous ice, which in turn becomes denser. This ice is more or less distinctly stratified, or in banded layers, resulting from

successive falls, or annual deposits, having somewhat different consistencies, or being separated, or outlined, by films of wind-blown dust or earth. See Fig. 94.

Movement; the Glacier Formed. — If we follow the névé down its slope, toward the valley below, there comes a point in the mass of accumulated ice, which may be 1000 feet, or even much greater in thickness, where *movement* begins, and the ice commences to flow slowly down the valley which forms the outlet of the catchment basin above, somewhat after the manner of a river. It flows down

Fig. 94. — Bergschrund, and beginning of the glacier. Mont Blanc region, Switzerland.

the valley to a point where, eventually, it is melted and changed to a river, which carries off the surplus drainage of the basin. The flowing tongue of ice projecting from the upper snow-fields is the glacier proper. Thus in regions above the snow-line, where the annual precipitation is mainly in the form of snow, the drainage, for a certain distance, takes place in part in the form of ice, giving rise to glaciers.

The point at the surface where the névé ends and the ice of the glacier is exposed, is at the snow-line of that place. This is usually considered the point where the glacier proper begins, but movement in the ice underlying the névé fields commences far above this. Very often there is a wide and deep crack, or fissure, or a number of them, between the ice of the snow-field and the adjacent rock surfaces of the catchment basin, or the thinner part of

the névé field lying on them. This is caused by the initial movement of the ice mass, and is known as the *bergschrund,* as illustrated in Fig. 94.

Not every snow-field forms a definite glacier; frequently it is not sufficiently large to produce ice enough to cause movement to be generated by its mass. It is simply an area of névé, passing into ice below. Such snow patches are common in all high mountains, and in some regions, as in Colorado for example, where the combination of mountain heights and amount of precipitation is not capable of producing snow-fields large enough to form glaciers, they alone are to be found.

Another stage is where the névé fields are sufficiently large to form at their lower ends ice masses which show by various features that movement or

Fig. 95. — A glacieret. The Dana glacier in 1883. Mt. Dana, Sierra Nevada, Cal.

flowage takes place, but not on a scale which enables the ice to project any distance below snow-line, or to produce distinct ice tongues flowing down into the drainage valleys. Such masses are variously called *glacierets, hanging glaciers,* or sometimes *cliff glaciers,* when nestled in the face of a cliff. Every gradation exists between simple névé patches, glacierets, and glaciers proper. The so-called glaciers found in the Rocky Mountains and in the high Sierras in the United States are nearly all glacierets, although a few are intermediate between these and real glaciers, of what, as we shall see later, are called the valley type. An example is seen in Fig. 95.

A *reconstructed,* or "recemented' glacier is formed where the movement carries a glacier over a cliff, and the mass of fallen fragments below is molded by weight and refreezing into a solid mass, which flows onward as a new glacier.

Lower Limit of Glaciers. — The point to which a glacier may descend below the snow-line before being melted depends on several circumstances. It is obviously a question between the rate of supply and that of melting, and might be likened to the distance a rod of ice could be thrust into a furnace before being melted; this would depend on the size of the rod, the rapidity with which it is pushed forward, and the heat of the furnace. Thus in tropical and warm regions glaciers, in general, project but a short distance below the snow-line; as we go farther north, although the snow-line descends, we also find glaciers pushing downward a relatively greater and greater distance from it; and, eventually, as we approach sub-arctic regions, we discover them entering the sea, and ending by breaking off in icebergs. The lower limit is also influenced by climatic conditions for, in moist regions, there is a greater precipitation and supply, hence glaciers are larger, more rapid, and descend greater distances below snow-line. Locally also, in a given region, a large glacier, especially if confined to a narrow channel, descends lower than a small one. As with rivers, so in these streams of ice, if they can go far enough, as in Arctic regions, the ultimate limit is the sea.

In the Alps glaciers project as far as 5000 feet below the snow-line, and in Norway nearly an equal distance. In southern Alaska they come down to sea-level at about 55° N., and also in southern Greenland at about 60°, whereas in Norway, which extends up to 70° N., they fail to enter the sea owing to climatic influences, especially of the Gulf Stream, see page 94. In the southern hemisphere, in New Zealand, which has many fine glaciers in the Southern Alps of the South Island, they descend in latitude 45° S. into sub-tropical forests in which the tree-ferns spread their graceful foliage, and in southern Chile, fed from the Andes, they touch sea-level about 47° S.

Classes or Types of Glaciers. — According to the size and features which they possess, the ice-fields of the land surface of the world may be divided into three great classes, or types: *valley*, or Alpine, glaciers; *piedmont* glaciers; and *continental* glaciers, or ice-caps. Each of these may be considered separately with examples, since each is of importance in the character of the geological work which it performs, as will appear presently.

Valley Glaciers. — These are of the class which has already been described in the foregoing, and are essentially the type one commonly has in mind when glaciers are mentioned. They consist essentially of a catchment basin, or area, for the gathering of snow above, Fig. 96, which feeds a stream of ice flowing slowly down a valley, and which is the glacier proper, Fig. 97, until through melting

Fig. 96. — View illustrating the lower limit of glaciers in the Alpine type. Glacier proper begins where snow-line ends. Glacier des Bossons descending from Mont Blanc, Chamounix, Switzerland.

Fig. 97. — Typical valley glacier with branches; lower part of the Mer de Glace in 1875. Moraines of earth are seen on its surface as dark bands. Chamounix, Switzerland.

it changes to a river. Such glaciers may be compared to rivers, and, as we shall see presently, they have many points in common with them, and some marked dissimilarities. Like rivers, they may have tributaries, that is, they may be formed of a number of ice streams flowing together and coalescing in a final trunk glacier, as illustrated in Fig. 97. They are the kind of glacier found in the Alps, where glaciers were first studied, and hence are often called Alpine glaciers; they are the ones characteristic of all high mountain regions, rising above the snow-line.

It has been estimated that there are about 2000 glaciers in the Alps; although most of these are small and of less than a mile in length, a few are from three to five miles, and one is ten miles long. The average thickness is probably a few hundred feet, the width in the largest a mile. In Norway there are several large plateaus of ice which send down glaciers in several directions into the valleys below. In the United States valley glaciers of some size are found only on the lofty volcanic peaks of the Cascade Range in northern California, Oregon, and Washington, as on Mts. Shasta, Rainier (Tacoma), Hood, Baker, Three Sisters, etc. On Shasta they attain a length of two miles, on Rainier they are larger, up to nearly seven miles. Fine glaciers are found in the mountains of British Columbia, and northward into Alaska, where they are of great size, the Seward glacier being stated as 50 miles long and three miles wide in its narrowest part.

In addition to the various regions previously mentioned, magnificent glaciers, up to 30 miles in length, are found in the Himalayas, while the Caucasus, Nan Shan, and other high ranges of Asia, except the Altai, furnish fine examples. On the high lands and islands of both the Arctic and Antarctic oceans they abound, and even in Africa, under the burning equatorial sun, small ones exist on Kilimandjaro (20,000 feet), and on Kenia (19,500 feet), and in South America on the high Andes of Ecuador.

Piedmont Glaciers. — If valley glaciers, or a number of them, descend far enough out of the mountains into more level country below, they may give rise to a large area of nearly stagnant ice before melting. Such an ice-field is known as a *piedmont* (foot of the mountain) glacier. If we compare valley glaciers to rivers a piedmont glacier might be likened to a lake, a place where the excess of ice through flowage becomes ponded, before melting from its surface and borders. Such glaciers are not common, and are confined to regions of high latitudes, the best known being the Malaspina glacier in Alaska.

The expanded foot of the Rhone glacier shown in Fig. 107 may be considered as the beginning of a piedmont glacier, and illustrates the principle of its formation.

The Malaspina glacier is situated at the foot of Mt. St. Elias (18,000 ft.) and

other high mountains, which feed it by their ice streams. It covers an area of 1500 square miles, and is from 1500 to 1000 feet thick. As may be seen from the map, Fig. 98, it closely borders the sea. It has a nearly level, broadly rolling surface, broken by innumerable fissures. Its borders are covered with earth and stones, like those of other glaciers and described later under moraines (p. 134), and these deposits in places are deep and extensive enough to support areas of dense forest growth, although resting on ice 1000 feet thick. By its melting the glacier gives rise to several rivers, the delta of one of which is seen in Fig. 43.

The Muir glacier in southern Alaska, at the head of the inland passage, may be taken as a type intermediate between the piedmont and valley glaciers. It

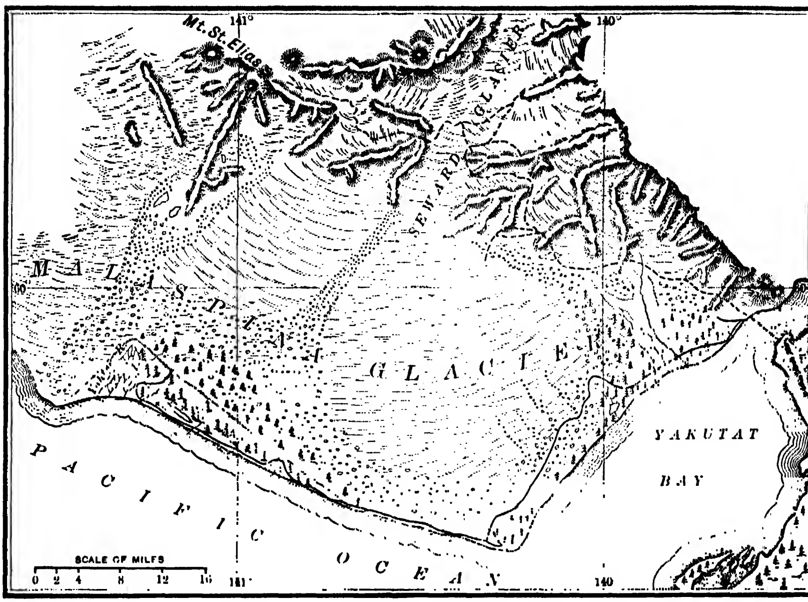


Fig. 98. — Map of the Malaspina glacier, after I. C. Russell.

fills a great basin of about 350 square miles and is fed by ice streams coming from the high mountains which surround it. The lower end of the valley basin touches the sea and, like a lake with accelerated movement of the water at its outlet, the ice in motion discharges into the head of Glacier Bay between mountain walls, forming an ice-cliff two miles long, from which icebergs are continually breaking off, with an uproar like heavy thunder. At the time of the writer's visit in 1887 the ice-cliff rose to a height of about 250 feet out of the sea; the depth in front, as ascertained by soundings then made, was over 700 feet, so that the thickness of ice was not less than 1000. A view of this ice front is seen in Fig. 99. The Muir is one of the largest of what have been called "tide-water" glaciers, those which reach the sea.

Continental Glaciers; Ice-caps. — These, as their name implies, are ice sheets of vast extent. If the two former classes of glaciers

may be compared to rivers and lakes, these may be termed seas of ice. Their chief feature is the almost endless monotony of broadly rolling, nearly level surfaces of wind-swept ice which they present, a monotony varied only by the continually successive storms of snow which maintain them. Near their borders they are often varied by occasional mountains of rock, rising like islands through the ice and known as *nunataks*. At their borders they thin down into prolonged lobes, or give rise to definite streams of ice which discharge into the ocean, forming icebergs. Only two examples of

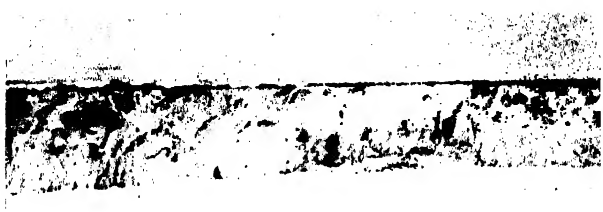


Fig. 99. — Sea-cliff of the Muir glacier in 1887.

them exist today, in the ice-caps which cover Greenland and the continent of Antarctica, upon the latter of which the South Pole is situated.

The ice-cap, or inland ice, of Greenland covers an area of probably 500,000 square miles. It has been traversed by Nansen and Peary and, according to these explorers, the great shield of ice rises to a height of 8500 feet. Its thickness is not known, but may be several thousand feet. This ice is in motion, as shown at its edges, where it becomes more rapid as it descends in valleys to the sea, but the movement in the interior must be almost indefinitely slow.

The size of the Antarctic ice-cap is not known, but it may be a million or more square miles in area. It has been partly explored by Amundsen, Scott and Shackleton in their journeys to reach the South Pole. It attains a height of 9000 feet. Like the ice sheet of Greenland it thins towards the sea, and descending through valleys in the mountain rim gives rise to huge moving glaciers. According to Scott it pushes off the land, and, advancing on the sea, covers the latter over vast stretches with a floating field of ice, known as the 'Great Ice Barrier,' from whose front, by their breaking off, the great tabular bergs of the Antarctic Ocean are formed. Other great ice-caps similar to these have existed in the past, but have melted and disappeared. This is clearly shown by the geological work they performed, as we shall see later.

Various Features of Glaciers

Movement. — The movement of glaciers, as compared with rivers, is very slow. Their motion was not generally known until the early part of the last century when it was observed that a hut built upon one of the Alpine glaciers changed its position, and the amount of change and the rate were measured. Since then this subject has been much studied, and a great deal learned concerning the nature of the motion of ice in glacial flowage. In the Alps the glaciers have, in general, been found to move from one to three feet a day, or from about 300 to 1000 feet a year, and this may be taken as about the rate of ordinary valley glaciers. The Muir glacier at its outlet has been found to move seven or more feet a day, or at a rate of 2500 feet per annum, while some Greenland glaciers have been measured up to 60, or even more, feet per day, but in these cases the ice of great interior areas is pushed with accelerated motion through valley openings into the sea. It has been found that the rate is influenced by several factors; thus it increases with a steeper slope and smoother bed; it is faster when the ice is thicker, and it is more rapid in summer, when it is warmer and the ice is melting, than in winter; the gradient, the thickness of ice, and the temperature are thus the chief things which affect the rate of motion.

Differential Motion. — One of the most important facts which has been discovered in regard to the motion of a glacier is that it is not the same in all parts of its mass. The glacier does not move by sliding down its bed as a whole, bodily, like a cake of ice off the roof of a house. This is evident since they often move on slopes elevated only a few degrees from a level surface, and in the case of the great ice-caps the flowage probably takes place outward from the center owing to the thickness of the accumulated ice mass, as much as, if not more than, because of the slope of the land. It has been found by driving rows of stakes aligned across the glacier with some point on either side, and observing their line, that, after a lapse of time, the line is curved downstream and therefore the center moves faster than the sides. In a similar way, on an exposed side of the glacier, a vertical line of pegs proved that the top moves faster than the bottom. It has also been observed that there is a line of swiftest motion, more sinuous than that of the valley in which the glacier lies, or that curves in its banks reflect the current back and forth, as in a river. (See page 66.) The motion of the ice is therefore *differential,* that is, some parts of the ice are moving over and

past, and therefore faster than, other parts. In these respects a glacier is like a river, and the ice indeed appears to move as if it were a thickly viscous fluid, like pitch or asphalt, which, though brittle enough to be broken by a sudden blow, yields under the pressure of its own weight, and undergoes slow flowage.

Origin of Glacier Motion. — The behavior of ice in exhibiting flowage in glaciers has been the subject of much investigation and discussion. It is clear that the force which causes it is the weight of the ice, due to gravity, and this vertical downward force may be resolved into components, one of which tends to thrust the ice in the direction of the slope on which it lies. It is also clear from the differential motion that the ice is not sufficiently rigid to resist this thrust, but is plastic in response to it, moving over itself, and dragging the whole mass downward. It is also known that glacial ice has a granular structure, consisting of interlocked crystal grains, which may be as large as peas or larger, and is thus in its texture like granite or some other similar rock.

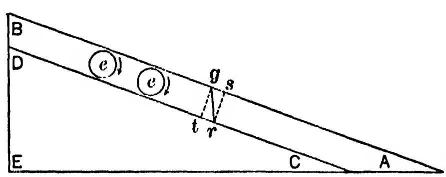


Fig. 100. — Diagram to show force causing glacial motion.

The granular condition begins in the névé fields and persists, the granules becoming compacted together into solid ice, but growing larger. In the compact massive ice of the glacier the fact that it is composed of irregularly shaped granules closely fitted together, like a rock, is not perceptible to the eye, but the structure may be clearly seen when a thin sheet of the ice is placed in an apparatus suitable for observing it in polarized light. Each grain then, in general, appears of a different color from its neighbors, and the structure is plainly blocked out. At the lower end, also, through differential melting, the grains may fall apart into gravel or sand-like heaps.

The influence of gravity on glacial motion may be considered as follows: let *ABCD,* in Fig. 100, be a portion of a glacier resting on the slope *CD*. Let the vertical line *gr* in its direction and length represent the force of gravity acting on it. Draw *gt* and *sr* perpendicular to *CD* and *AB*. In the parallelogram of forces *srgt* the component *gs* represents that portion of the force of gravity which thrusts the ice in the direction *BA*. The resistance to this force is composed of the friction on the bed *CD* and the backward thrust of any surface *AC*. If a mass ABE were entirely composed of ice resting on a level surface *AE,* the tendency of a particular layer *ABCD* to move in the direction *BA* in response to the thrust *gs* would be opposed by the resistance to shearing along the line *CD*. The differential motion which occurs shows that this resistance is not sufficient to withstand the thrust. Since the ice is

composed of grains, these grains tend to revolve as shown in the diagram, e and e; this tendency is resisted by the irregular interlocked form of the grains and the rigidity of the crystal ice composing them.

Apparent Viscosity of Ice. — It was formerly thought that ice was a viscous substance, and that when in mass it exhibited the property of slowly yielding to its weight and of flowing, that such bodies possess, as seen in pitch and asphalt. This apparent behavior of the ice in a glacier has been mentioned previously. We now know that, however much ice may apparently show this property, it is not, and cannot be, truly viscous, and that the apparent viscosity must be explained in some other way.

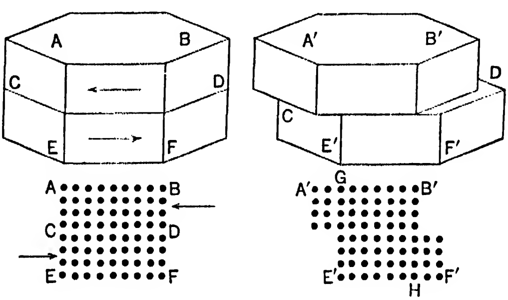


Fig. 101. — Diagram illustrating gliding planes in an ice crystal. The lower figures illustrate the molecular structure in a vertical plane.

The difficulty in entertaining this view of viscosity is that ice is crystalline in structure, and in crystals the physical molecules are arranged in definite geometrical positions in space with respect to one another, and to break up this arrangement would destroy the *physical* identity of the substance, as when ice changes to water. In a viscous substance the molecules on the contrary have no definite arrangement, and can occupy any position with respect to one another without destroying its physical state. This is a fundamental property of liquids, and viscous substances may be regarded as very stiff liquids. Cold molasses is a good example of a viscous fluid. Hence ice, being crystalline, cannot exhibit the property of true viscosity.

Explanation of Glacial Movement. — A variety of different theories have been proposed to explain the apparent viscosity of ice and glacial motion, which it would be beyond the scope of this work to discuss. We must, therefore, content ourselves with what, in the light of our present knowledge, seems the most probable explanation. This depends on two properties of ice; first, that ice below the freezing point if subjected to sufficient pressure will melt and, if the pressure is removed, will refreeze; and second, that in a

certain direction one part of an ice crystal can be pushed over another part of the crystal, without destroying its crystalline nature.

With regard to the first, the freezing point of water is lowered by pressure. This depends on the fact that water expands in changing to ice. Thus under atmospheric pressure water freezes at 32° F.; if we put sufficient pressure upon it the temperature may be lowered to 30° and, since it cannot expand into ice, it will still remain liquid; should the pressure be removed it will at once freeze. Conversely if we place ice under sufficient pressure at a given temperature, say 31° F., it will contract by turning into water; if the pressure be relieved it will immediately revert to ice. At the bottom of 5000 feet of ice the melting temperature is about 30.2° F., or — 1° C.

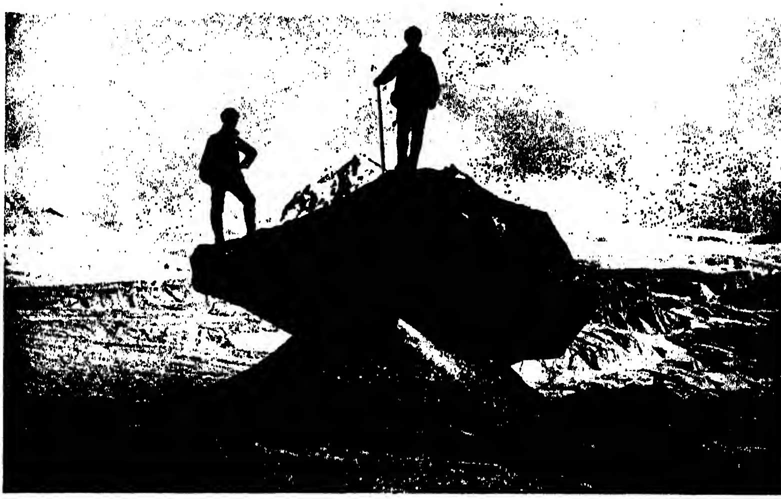


Fig. 102. — Erratic block mounted on ice pedestal; caused by differential melting. Switzerland.

With regard to the second property it has been found by experiment that ice crystals have the quality, when subjected to a sufficient shearing force in a certain direction, as along the plane *CD* in the crystal *ABEF*, Fig. 101, of the molecules being able to slip, or *glide*, along this plane and change position without destroying the physical condition, or cleaving or breaking the ice. Thus the part *GB'HE'* in Fig. 101, illustrating the molecular structure, is as firm and solid an ice crystal as before. This slipping can take place between any layer of molecules in a plane parallel to the base of the hexagonal prism, but not in any other direction. *A'F'* represents a crystal thus partly deformed. A crystal which has this property is said to have *gliding planes;* it is possessed by various substances, such as the common mineral calcite, $CaCO_3$.

In applying these properties to explain glacial movement we can see that the resistance to revolution, which, by the thrust of gravity, would generate forward motion of the interlocked crystal grains of

ice, as a mass of shot would flow down an inclined trough, may be overcome by the pressure. The minute points of resistance on each grain may be momentarily liquefied by the pressure, aided by the heat of friction, the grain revolved more or less and changed in position, and, the stress being relieved, the water would immediately resolidify. And, whenever a grain happens to be in the right position, so that the thrust is in the direction of the gliding planes, motion will take place along them also. Since the latter is the easier way of relieving stress, whenever a grain comes into this position it is likely to stay there, and hence in the lower part of the glacier, and towards its end, the crystals are largely in parallel position and the movement is chiefly along gliding planes. Thus by a combination of melting and refreezing under pressure, and by slippage along gliding planes, the granules are able to change position, and the ice to thus undergo a slow flowage which simulates a viscous motion.

Surface of a Glacier. — The surface of a glacier is not ordinarily smooth and unbroken like that of a frozen river; on the contrary it usually has a variety of features which make travel over it extremely difficult. Aside from minor irregularities produced in a variety of ways by unequal melting, one phase of which is illustrated in Fig. 102, the ice is traversed by wide and deep cracks called *crevasses*, and covered in places by accumulated heaps of earth and stones termed *moraines*. Each of these deserves consideration.

Crevasses. — These fissures may have any width, up to 20 feet, or even more, and of great depth, 100 feet or greater. The most prominent ones are *transverse* to the course of the glacier and are caused by the passage of the ice stream over a salient angle in its bed, with change from a lesser to a greater gradient, as illustrated in Fig. 103. When the ice passes over such a prominence, tension is produced, greater in the upper than in the lower layers of ice; the latter yields to the tension and cracks; the fissures yawn widely at the top and gradually close below. They also curve downstream, since the motion is swifter in the center, and this tends to bend them. Even a change of angle in the bed of only two or three degrees produces crevasses, a striking proof that ice is not a truly viscous substance. Where a very steep gradient is encountered the ice is much broken and an *ice-fall* is produced, as illustrated in Fig. 107 of the Rhone glacier. The pointed jagged masses of ice made by crevassing are called *seracs*.

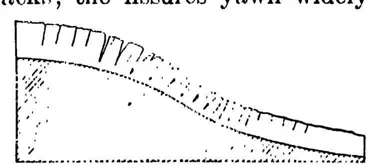


Fig. 103. — Diagram to show the formation of crevasses.

Crevasses also occur on the margin where the ice drags against the inequalities of the side walls of the valley. These *marginal* crevasses point inward and upward at about 45° with respect to the course of the glacier. *Longitudinal* ones also occur in the terminal lobe of the glacier where the ice, relieved from transverse pressure, tends through lateral spreading to fall apart, as illustrated in Fig. 107. The first crevasse which forms in the névé field, and which shows the initiation of movement, is called the bergschrund, as previously mentioned, page 123. The transverse crevasses once formed do not remain indefinitely, for on moving over a salient angle the ice generally passes into a re-entrant one, as illustrated in Fig. 103, the tension is replaced by compression, which more or less closes the fissures, the ice blocks refreeze, and the crevasses may be obliterated, though generally not completely, owing to enlargement by melting. Thus the glacier in its course is subjected in places to crevassing, which may disappear elsewhere, somewhat as a river at its rapids may display foamy water, not elsewhere seen.

Moraines. — In an ordinary valley the débris of earth and stones, which is produced as a result of the weathering and erosion of its sides and walls, would form slopes and talus slides, which passing downward by creeping would be ground up by the stream and borne away. In a valley more or less filled by a glacier this material descends instead upon the ice and is taken along by it as bands of heaped-up material. Sometimes, however, it falls into the bergschrund and, becoming frozen into the ice, is carried away. Moreover, the ice at the bottom of the névé fields, being frozen into cracks and cavities, and around projections in its stony bed, when motion begins, "plucks" or quarries masses of rock and takes them forward with it. All the material thus obtained and transported by the glacier serves to form the moraines. If the material is carried on top of the ice it is spoken of as *superglacial;* if frozen fast within the ice, as *englacial;* if transported fixed in the bottom of the glacier, as *subglacial.* In the upper névé fields, since these are covered by successive snowfalls, there is little superglacial material; in the lower part of the glacier proper, as melting and waste become more and more pronounced, a greater and greater quantity of englacial material appears at the surface and becomes superglacial.

Moraines are generally divided into four classes, according to the position they occupy with respect to the glacier, as *lateral, medial, ground,* and *terminal. Lateral moraines* are formed along the sides as explained above. They become larger and more evident toward the terminus, forming ridges of earth and stones, 25,

50, or even 100 feet high. The *medial moraines* are made of the lateral ones when tributaries come in, as illustrated in Fig. 104, and they may be seen in the view, Fig. 97. There may be as many as eight or ten of them. At the lower end, through melting, as mentioned above, englacial material appears at the surface and gives rise to new medial moraines. See Fig. 104. The *ground moraine* consists of the débris carried along at the bottom of the glacier. All of the material transported by the ice is eventually dumped at its end in a confused mass of earth and stones which forms the *terminal moraine*. This may coalesce with the lateral moraines as indicated in Fig. 104. Finally it must be remembered that through the longer part of its course the greater part of the material is in and under the ice.

Fig. 104. — Plan of a valley glacier, showing tributaries and terminal lobe; *ll*, lateral moraines running into *tt*, the terminal moraine; *mm*, medial moraines. As melting progresses, more and more material appears; *s*, exit of subglacial stream; *vv*, valley train of water-laid débris.

Veins and Layers. — The ice of glaciers frequently has a veined, or marbled, appearance due to bands of ice varying in color from blue to white. The white ice is full of minute air bubbles which produce the color; the blue is free from them. The veining is formed at places of greatest compression, as where the ice moves into a re-entrant angle in its bed, and the pressure squeezes the air out of the white vesicular ice, turning it into blue, which the onward motion streaks out.

In the lower part, where the thrust from gravity is most pronounced, the ice often shears and is pushed over itself, forming a series of distinct layers, or bands. This banded appearance is often greatly enhanced by layers filled with dirt and gravel, which contrast with others of clearer ice. This often gives the glacier a resemblance to beds of stratified rock, as illustrated in Fig. 105.

Drainage; Subglacial Stream. —Within a glacier, in the region above snow-line where it is growing, the temperature must be below the melting point; in the lower part, where it is wasting, at the melting point. Hence melting is generally going on all the time; in

summer it is melting rapidly at the surface, and is traversed by streams of water, which fall into crevasses, or form pools on its surface. All of this water eventually descends to form a stream under the glacier, which issues at its lower end, sometimes from an ice-cave, sometimes from along one side, and thus carries off the general drainage of the valley, Fig. 106. Such streams are very turbid, being heavily charged with sediment, and as this sediment consists of fine particles of fresh, unweathered rock, ground up by the glacier on its bed, they are chiefly white in color and give the stream a peculiar milky appearance, which it may retain for long distances. This milky look is so characteristic as to lead to the suspicion, when seen in a river, that it is fed by melting glaciers higher up in its course.

Fig. 105. — View illustrating the veined structure of a glacier, simulating folded rock strata. The situation is at the end of the glacier, and the subglacial stream may be seen appearing, and also morainal material. Greenland. W. H. Brewer.

Advance and Recession of Glaciers. — We know in a variety of ways that great changes of climate have occurred in the past, as will be fully discussed in the historical part of this book. These changes have been not only general, but also local, as affecting some particular region, and have already been mentioned in one aspect under the history of salt lakes. Such changes have a profound effect upon the existence of glaciers. Thus we know from evidence, to be shown later, that in recent geological times North America and Europe were covered with great continental glaciers, or ice-caps, similar to that of Greenland to-day, as far south as Ohio and middle Germany. At the same time the valley glaciers of the Rocky

Mountains and of the Alps had a vast extension over their present size. With change of climate these ice-caps have disappeared, and valley glaciers have in some places greatly shrunken and in others melted away.

But aside from these great changes, occupying periods of geologic time, glaciers appear to grow and advance, or to diminish and retreat, in response to varying climatic cycles of years of greater precipitation and coldness, compared with ones of greater sunshine and

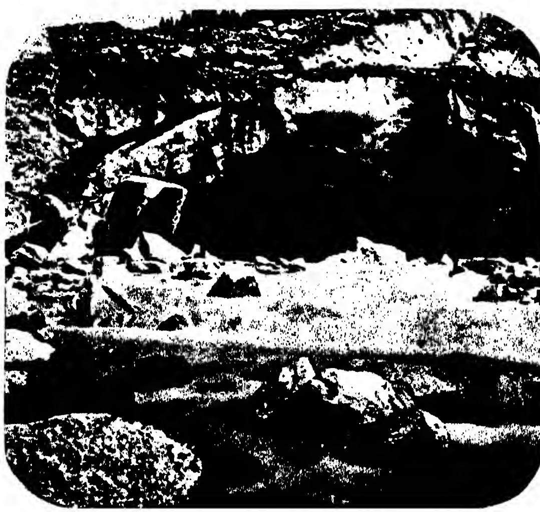


Fig. 106. — Subglacial stream and ice-cave. Morainal material is seen above which falls as the ice melts and helps to build the terminal moraine. Transported blocks fill the bed of the turbulent stream which carries the finer earth and ground-up rock away. Chamounix, Switzerland.

warmth. Thus the glaciers of the Alps, during the past century, have been observed in a number of cases to have experienced such oscillations, but up to the present an insufficient amount of accurate data, relating to this phenomenon, has been gathered to enable us to state definitely the periods, and the laws governing them, and whether on the whole, irrespective of these periodic oscillations, glaciers the world over are diminishing or not. At the present time in the Alps and in North America they are in general retreating, as illustrated in Fig. 107 of the Rhone glacier. In 20 years since 1887 the Illecillewat glacier, one of the valley type in British Columbia, was observed to have retreated at least 500 feet. Some individual

glaciers in the Alps and in Alaska, on the other hand, have been shown to be advancing. In 1899 central Alaska was visited by a heavy earthquake which shattered the ice of many glaciers in that region. In some of the land glaciers this caused a rapid advance of the ice, but in tide-water glaciers, like the Muir, see page 127, so much ice was broken from the front and floated out to sea, that notable retreats of these fronts took place; of a number of miles, in two or three years, in the case of the Muir.

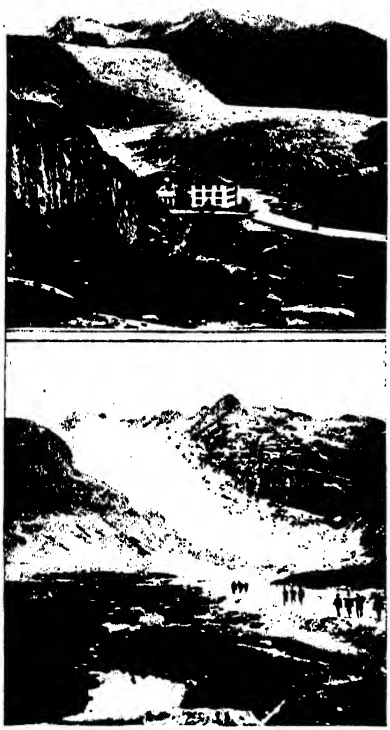


Fig. 107. — Two views of the Rhone glacier, Switzerland; the upper one taken in 1870, the lower in 1905, which illustrate the retreat of the ice in 35 years. The older one shows the terminal lobe and longitudinal crevasses.

Geological Work of Glaciers

The work of glaciers, like that of rivers, consists in *erosion, transportation* and *deposition.* While in these features, speaking broadly, they are like rivers, the manner in which the work is done and the results achieved are very different, as will appear from the following discussion of them. Our knowledge in this case is obtained by observation of living glaciers, of areas which they have uncovered and abandoned in recent retreats, and by application of the facts thus learned in regions in which they no longer exist, but which these evidences show they once occupied.

Glacial Erosion. — In its highest part, under and at the edges of the névé slopes, a glacier erodes chiefly by "plucking" and gathers its load by this process, and by collecting the débris coming to it through the weathering of the slopes above the snow, as described under moraines. The work of gathering is especially active in the bergschrund, where this crevasse comes between rock and snow; in summer time thawing takes place during the day, the rocks are wet, and freezing is apt to occur at night, springing out blocks which fall

down to be enveloped by the ice and carried away. Thus, over the area where the névé fields rest, they are constantly quarrying inward and downward, and in the long course of time this gives rise to partly bowl-shaped valleys, or basins, called *amphitheaters*, or *cirques*. These cirques are often cut somewhat deeper at the center than at the place of discharge and thus, when the valley is no longer filled with ice and snow, these depressions are occupied by one or more small ponds or lakes, as shown in Fig. 108. Such cirques are common features in the mountains of northern regions and exhibit the collecting basins of former glaciers. See Figs. 109 and 116.

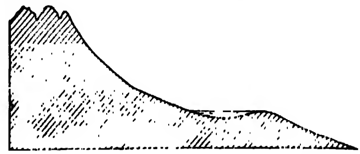


Fig. 108. — Section through amphitheater and glacial lake.

As soon as movement begins, the erosion is somewhat different. Plucking continues, but in addition the earth and stones frozen fast

Fig. 109. — View of glacial cirque or amphitheater. Sultan Mountain, Colo. F. L. Ransome, U. S. Geol. Surv.

into the bottom of the ice form a huge rasp, whose power is enormously augmented by the great weight of ice above. Thus in its moving course the glacier is constantly grinding away the rock-bed on which it rests. This grinding occurs not only over the bottom

of the bed, but along the sides of the glacier-filled valley as well, making a glacier, therefore, differ very markedly in erosion work from a river, as we shall presently see. The effectiveness of this engine of erosion depends largely on the rigidity with which the rocks and gravel, the teeth of the rasp, are held by the ice, and thus on the temperature; at the lower end when the ice is soft and melting it has been observed pushing over morainal material without disturbing it and this has sometimes given a wrong impression that glaciers are not very efficacious agents of erosion.

Glaciation. — The result of this work is seen on bed-rock, which is smoothed, rounded and polished as it is ground away, as in Fig.

Fig. 110. — Glaciated country rock, Eastport, Maine.

110, and scored with scratches and grooves, called *glacial striæ* running in the direction of glacial flow. See Fig. 111. These are made by pebbles, sand, etc., held firmly frozen in the ice. They may be very fine scratches or attain the dimensions of small channels, sometimes beautifully fluted. Projecting masses or hummocks of bed-rock, instead of showing angular, broken outcrops, are more or less smooth and rounded, often shaped like the half of an egg, especially on the upstream side, and these features are called *roches moutonnées*, a term adopted from the Swiss mountaineers in allusion to a fancied resemblance to the backs of a flock of sheep. Small lakes or pools may occupy rock-basins where depressions have been ground out of bed-rock. The process of producing such characteristic features is called *glaciation*, and a country which exhibits them is said to have been *glaciated;* they are seen when glaciers have retreated, or disappeared, and by their presence we are able to recognize the former existence of such glaciers, in regions where these have long since vanished, as in New England, for example.

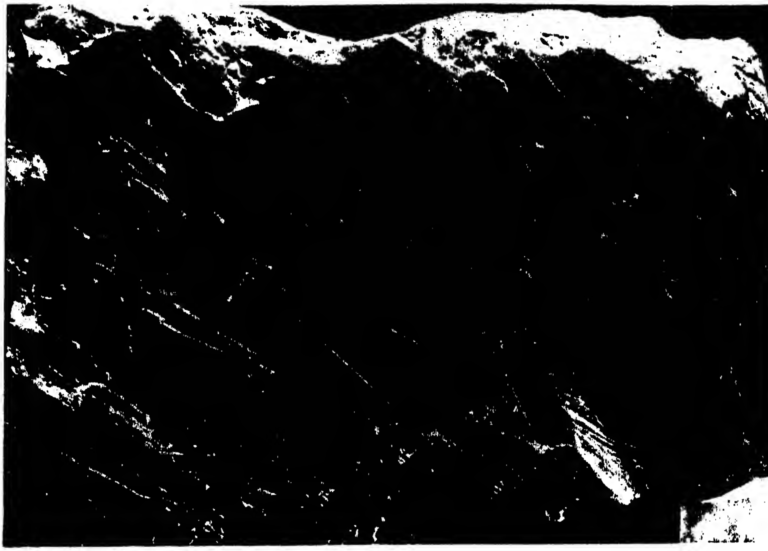


Fig. 111. — Glacial striæ; scratches and groovings made by moving ice on limestone bed-rock. Near Rochester, N. Y.

Glacial Valleys. — The effects of glacial erosion are seen, not only in the smaller details mentioned above, but also in larger features, such as affect the topography of valleys. The normal shape of a river valley produced by corrasion and weathering, has been discussed on page 49 and shown to be that of a V in section. In a valley more or less filled with ice the longitudinal erosion takes place, not only on the bottom, but also along the sides, and hence a well glaciated valley has normally a U shape in cross section, as seen in Fig. 112. In a river valley the tributaries, and the ravines they have made, normally join the main stream and its valley bottom at grade; in a glaciated valley the tributary glaciers cannot cut as fast as the main one, and the mouths of their valleys are ground back, and end high up on the wall of the main valley into which they discharge in cascades. Such *hanging valleys*, as they are called, with their

Fig. 112. — Characteristic U shape of glacial valley. Kern Valley, Cal. H. Gannett, U. S. Geol. Surv.

Fig. 113. — A hanging valley and falls. Yoho Valley, British Columbia.

water falls are common features in the scenery of the northern Rocky Mountains, in Switzerland, and in Norway, and are illustrated in Fig. 113.

In a river valley the spurs between ravines run down and die out at, or near, the river; in a glaciated valley, these are ground away by the longitudinal erosion up to the level of the ice and after its recession terminate in more or less well defined inverted V shapes in the wall of the main valley; these spurs are said to be *facetted*. Thus U-shaped sections, hanging tributary valleys, and facetted spurs are characteristic features of the topography of glacial valleys. The change of a normal river valley into a glaciated one exhibiting them, by ice invasion and retreat, due to climatic changes, is seen in Figs. 114, 115 and 116.

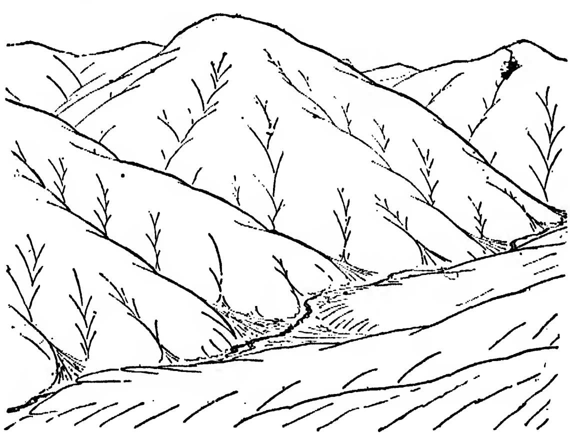


Fig. 114. — A mountain mass, normally eroded by weathering and running water and unaffected by glacial action. The valleys and ravines are V-shaped in section. W. M. Davis.

Glaciation by Ice-caps. — In the great continental ice-caps the ice appears to move *en masse* over broad areas away from the general center of dispersion and regardless of the minor features of

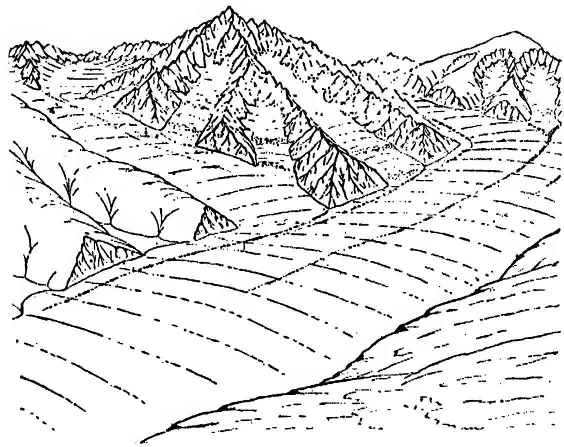


Fig. 115. — The same mass as in Fig. 114 strongly affected by glaciers which occupy the valleys. The rugged topography above the ice, produced by weathering and frost should be noted. W. M. Davis.

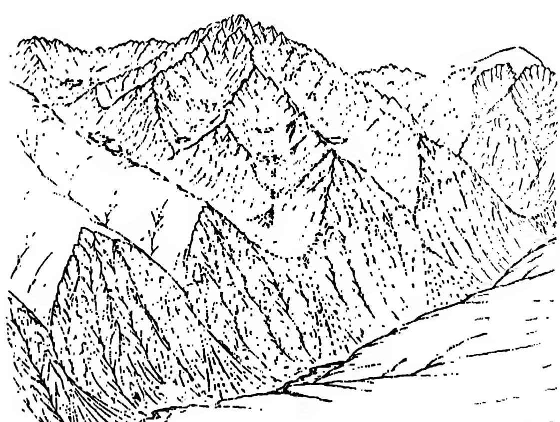


Fig. 116. — The same mass of mountains as in Fig. 115 after the retreat and melting of the ice. Note the nature of the topography, the trough-like form of the glaciated valleys, the amphitheaters, some with lakes, the hanging valleys, and the facetted spurs. W. M. Davis.

underlying topography. Hence on their retreat we find the glacial striæ, which indicate the direction of flow, pointing in the same way over wide areas, and down, up, and across valleys. However, it has been noticed that valleys running somewhat in the general trend of flowage, have in places exercised some control and given rise to local sub-currents in the ice. Where the ice-caps end in mountain ranges and push down their valleys in projecting tongues to the lowlands, or the sea, they exhibit the erosional features common to valley glaciers. Striated and polished bed-rock, roches moutonnées, and rock-basin lakelets over wide stretches of country are the characteristic features of glaciation by the continental ice sheets.

The manner in which the Antarctic ice-cap pushes out to sea in the Great Ice Barrier, see page 128, naturally suggests that the work of glaciation must be going on beneath it for some distance below sea-level, until the point is reached where it must tend to float, and lose its effectiveness as an engine of erosion. The valleys leading seaward of the land buried under the ice must be ground out into glacial troughs, and eroded below sea-level. If the ice-cap should disappear, such "over-deepened" valleys would be filled with sea water and would form fiords (see page 104). Fiords, then, are a natural result of heavy glaciation, such as that produced by ice-caps, along coast-lines, or by powerful glaciers in high latitudes descending from the mountains into the sea. Unlike ordinary estuaries they are commonly limited seaward by a rocky threshold covered with shallow water and within this the water deepens sometimes to several thousand feet (Norway), before it again shallows inland. Such thresholds must mark then the limit of effective downward glacial erosion of the pre-glacial valleys.

Glacial Transportation. — There are no special problems connected with transport by ice, as compared with water. Whatever lies upon it, or is enveloped in it, regardless of size, is irresistibly borne along, and eventually deposited when the ice melts.

Glacial Deposits

Moraines. — The manner in which these are formed has been already described. As seen at the terminus of a glacier, or after its retreat, they consist of mingled heaps of earth and stones, sometimes several hundred, or, in exceptional cases, 1000 feet high, or even more, and wide in proportion. Unlike water-laid material, which is nicely assorted as to size and deposited in stratified layers, they consist of confused débris of all sizes tumbled together, as illustrated in Fig. 117, and this want of stratification is one of their distinguishing characteristics. Those pieces of stone which have been transported as sub-glacial material and have taken part in the erosive work of the glacier, have smooth, flat surfaces, or *facets*,

ground upon them, and are polished and striated, or scratched. In other words, they are *glaciated,* and such facetted, glaciated pebbles are characteristic features of glacial work, and of moraines. On the other hand, the pieces of rock brought down on, or in, the ice, not being subjected to grinding, are as rough and angular as when removed from the valley walls, and like those of any talus. The heterogeneous material forming the moraines is known as *glacial till,* or *bowlder clay.*

Since at its lower end, the ice moves not only down, but radially outward, as illustrated in Fig. 104, the terminal part of the lateral moraines may be so greatly increased by this movement that they may become of huge size; as the glacier retreats they continue to be left behind, or to grow, following after it. Thus they may be very large, while the terminal portion in front of the ice may be relatively small, or almost wanting. They are really laterally terminal moraines.

Fig. 117. — Glacial till or bowlder clay, consisting of the unassorted material of the moraine. The Caucasus.

Glacial Bowlders or Erratics. — Another characteristic feature of a country which has been glaciated is the presence upon it of scattered bowlders of all sizes and shapes, which are different in nature from the underlying bed-rock. They are transported blocks of rock which have been left from the melting of the ice; that they have been transported is proved by the difference between them and bed-rock. They are called *erratics* or *glacial bowlders.* They are not infrequently of great size, as large as a small house, as illustrated in Fig. 118. In some cases, through the gentle lowering by

the melting of the ice, they have been deposited in very insecure positions, and are known as *perched blocks;* they may be even so nicely poised that although of large size they may be rocked by pressure of the hand, and are known as rocking stones. Such deposition would be impossible by water and, in general, indicates the agency of ice, though they may sometimes be bowlders of disintegration, page 30.

Through peculiarities in the character of the stone, such erratic blocks have often been traced many miles, 5-100, or even more, to their parent ledges of bed-rock. The most striking instances of transported bowlders are those left

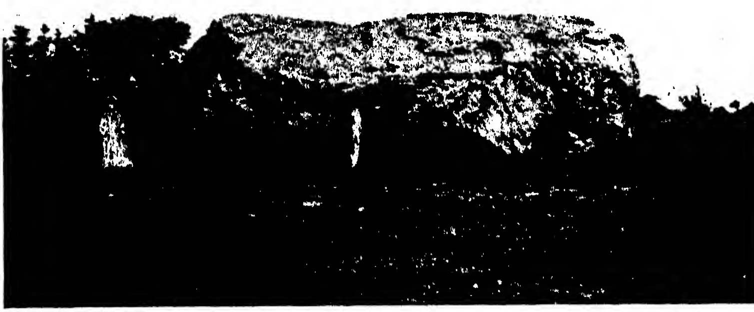


Fig. 118. — Glacial erratic, a transported bowlder of trap resting on sandstone; weight about 500 tons. New Haven, Conn.

by former ice-caps. In general the northern parts of North America and Europe are more or less covered with them. If they can be traced to the parent ledges, as in the case of the "bowlder train" of Richmond, Mass., they afford valuable indications of the direction of flowage, and confirm the indications left by the striæ on bed-rock.

Glacial Lakes. — In a country which has been recently glaciated, lakes are a common feature. The formation of small rock-basin lakes by irregular erosion of bed-rock by glaciers has been mentioned already. But a much more important way in which glaciers form lakes is by moraines left athwart valleys, which make dams, ponding back the drainage. Of the many beautiful lakes which lend charm to the scenery of the hilly and mountainous regions of North America and Europe, in the Adirondacks, in New Hampshire, Maine, Canada, the Alps and Norway, by far the greater part have been made in this way. See Fig. 119. These dams have mostly

been left in valleys on the retreat of the continental ice-caps. In the Southern States, which have been unvisited by the ice, lakes are rare, or wanting, as previously mentioned, page 81.

In some of the Northwestern States and Canada, as in Minnesota for example, the many small lakes are due, not to the damming of definite valleys, but to the filling with water of depressions in the irregular hummocky ridgy surface of the wide sheet of morainal débris left on the retreat of the ice-cap.

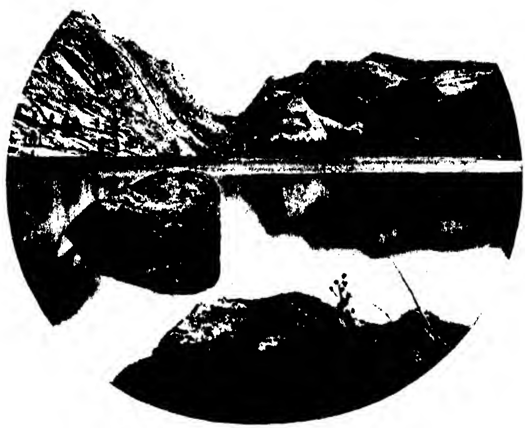


Fig. 119. — Lake due to glacial action. The topography in the background shows the characteristic forms and surfaces of glaciation. Sierra Nevada, Cal.

Thus glacial lakes are due to rock basins, to morainal dams in valleys, to hollows in morainal deposits, and to the filling with water of the kettles mentioned beyond.

Ice-Cap Deposits; Glacial Drift. — The deposits left by the continental ice sheets, or caps, are somewhat different from those of valley glaciers. As they have no side boundaries there are no distinct lateral moraines, but only the terminal one. The former edge of the ice is marked by this terminal moraine, a deposit of till crossing the country as a series of hills, hummocks, knobs, and ridges, with depressions between, called *"kettles,"* which are often filled with water. As the ice continues to retreat by melting, the material it contains is left as a broad sheet of till, or bowlder clay, covering the country. As the retreat apparently takes place irregularly, with oscillations of advance and recession, like those observed in modern glaciers, such stages are marked by new terminal moraines, which,

as they lie back of the most advanced one, have been called *recessional.* Certain peculiar forms of these glacial deposits have been called *drumlins;* they consist of rounded, elongated hills, or short ridges, of unassorted till, whose longer axis points in the direction of ice movement; it is not definitely known how the deposits assumed this form and position. They are especially common in central New York and in eastern Wisconsin, and are illustrated in Fig. 120. All the material, — the sheets of till, the moraines, erratic blocks,

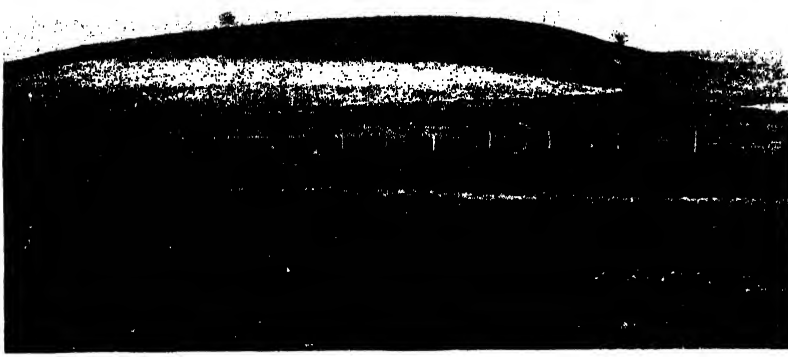


Fig. 120. — Drumlin near Newark, N. Y. G. K. Gilbert, U. S. Geol. Surv.

etc., — whose deposit on glaciated bed-rock, whose want of gradual transition into country rock, observed where soil is found in place, and whose foreign nature prove it to have been transported, and whose heterogeneous, unassorted character and glaciated pebbles show it to have been deposited by ice, is known under the general term of the *glacial drift.* This term is also applied to these materials where they have been transported or washed and laid down by water; in this case stratification is more or less distinctly shown in the deposits and they are commonly referred to as "modified" or "stratified" drift. These we will now consider.

Fluvio-Glacial Deposits. — The melting of the ice of glaciers and the natural drainage of the valleys occupied by them produce streams heavily charged with sediment, as described on page 136. The streams, unable to carry this material, deposit it on the valley floors, building up flood-plains, in which they wander in devious and shifting channels, and this deposit, sloping downward along the valley from the terminal moraine, is known as the *valley train.* In the

case of continental ice-caps the washed-down material, instead of being concentrated, as in a valley train, may be spread widely by meandering streams over broad areas, giving rise to what are known as *outwash plains*, or *frontal aprons*. Such deposits, since they are laid by water, are more or less distinctly stratified, while the pebbles of the gravels may become rounded through attrition, and lose more or less completely the facets and scratches they exhibit in the moraines. Fig. 121 shows a section of this water-laid drift resting on unassorted till.

In the outwash plains, conical depressions, sometimes 100 feet deep, are found which are called *kettles*. They are well illustrated in the sand plain above New Haven, Conn. They are supposed to be cavities made by the melting of isolated blocks of ice, left for a time by the retreat of the irregular glacial front, and then surrounded and more or less covered by sediment from the glacial streams.

Fig. 121. — Water-laid glacial drift on unassorted till. Columbus, Ohio.

Kames and Eskers. — These are peculiar forms of deposit made by the sediment-laden streams from the ice-caps. Kames are hills, knobs, or short ridges, sometimes attaining a height of 100 feet, which resemble drumlins, but differ from them in that they consist of stratified material and, instead of pointing in the direction of ice flow, they tend to arrange themselves athwart it. They are apt to occur in groups with depressions between which sometimes contain water. They are thought to represent crevasses, or other openings, or depressions in the irregular front of the ice sheet, which have been filled with sediments and left as projections upon its melting.

Eskers are long winding ridges of stratified sands and gravel, 10, 20, or even 100 feet high, with very narrow crests and trending in

the general direction of ice flow. They may strikingly resemble artificial railway embankments. While found in various parts of the Northern States, they are particularly striking in Maine. They have a great development in Scandinavia where they run across country, in some cases, for many miles. They are illustrated in Fig. 122. It is supposed that they have been built by streams which had cut channels for themselves on, in, and under the ice. The deposit would be confined by the ice walls, and, upon the melting and retreat of the ice sheet, would be left as a sinuous ridge, marking the former channel.

Fig. 122. — The esker of Punkaharju, Puruvesi, Finland. In Scandinavia such a ridge is called an 'ose,' plural 'osar.'

With respect to the deposits made and left by ice-caps the following table will enable the student to summarize the main features brought out in the above discussion.

Ice-laid, heaped

Moraines. Irregular ridges, when terminal, transverse to ice flow.
Drumlins. Ovate hills, elongate parallel to ice flow.

Water-laid, stratified

Kames. Round to ovate hills, grouped transverse to ice flow.
Eskers. Winding, very elongate ridges often parallel to ice flow.
Frontal aprons. Outwash plains, beyond morainal deposits.

Icebergs

Icebergs are formed in northern regions where glaciers come down from the land and enter the sea. Pushing out into the water, the buoyancy of the ice floats the end of the glacier and causes huge masses to break away, which float off as icebergs. The process is illustrated in Fig. 123.

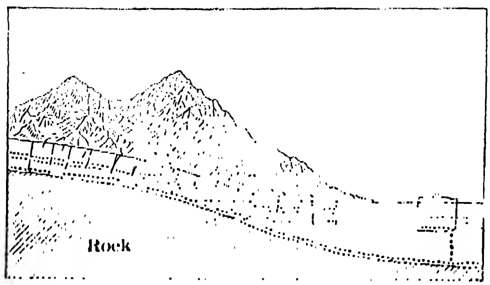


Fig. 123. — Diagram illustrating the formation of icebergs.

Icebergs are sometimes of very great dimensions, rising 200 feet or more above the sea, though this is uncommon. The specific gravity of solid ice is about 0.9, compared with water, but glacier ice is more or less porous, and perhaps as much as one-seventh of the mass of a berg may be above water. Thus they may extend downward 1500 feet; they have been observed aground in water of this depth. The volume of some bergs has been estimated to be as

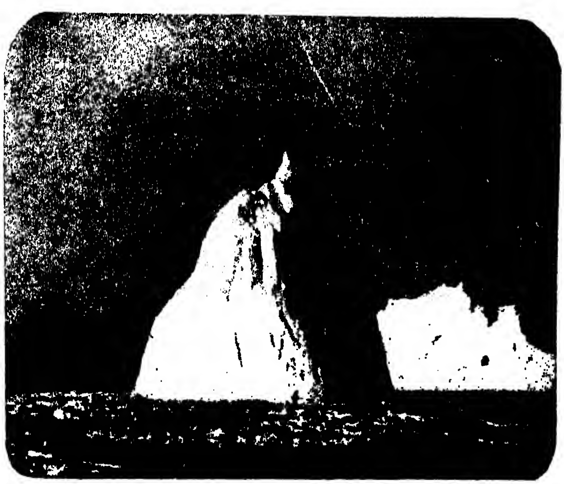


Fig. 124. — Icebergs in the Polar sea.' Only a small part of the berg is above water, but this may be the longest, thinnest part of the mass which projects, like the apex of a floating cone. It is surrounded by floes of frozen sea-water.

much as 500,000,000 cubic yards, which would cover an area of one mile square 500 feet deep. The largest bergs are those which break from the great ice barrier surrounding the Antarctic continent (see page 128); they are often remarkably tabular in form. The source of the North Atlantic bergs is chiefly the great ice-cap of Greenland, especially that prolongation of it into the sea known as the Humboldt glacier, which presents an ice-front, or cliff, 60 miles long. It should be remembered that icebergs are always composed of *fresh-water ice* and are made on the *land* by glaciers; the ice of the frozen sea itself forms ice-fields, called *floes*, which are not originally more than 8-10 feet thick, though by pressure, crowding, and over-riding, they may in places become several times this thickness.

By the general circulation of oceanic waters, which has been previously described, all the floating ice of high latitudes in both hemispheres is gradually drifted into warmer seas, northward and southward respectively towards the equator, and eventually melted. In the North Atlantic the bergs may be floated as far south as 40°, making a formidable menace to navigation. Were it not for this general law, ice would accumulate indefinitely in polar regions, until the greater part of the waters of the world were locked up in polar ice-caps, while the lands would be arid deserts.

Geological Work of Floating Ice. — In high latitudes the floating ice of the bergs and floes, driven against the shore by winds and tidal currents, chafes against the rocks, eroding and polishing them. Icebergs grinding on the bottom may also erode and scratch the rocks, but such effects are probably relatively small in amount. Icebergs, like other glacial ice, may contain englacial material, earth and bowlders frozen in the mass, which is dropped on the bottom as the berg melts. Although locally such deposits must be slight, in sum total the amount of material transported in this way must be large. Since the North Atlantic bergs are apt to go aground in the shallow water southeast of Newfoundland and melt, it has been supposed that the Grand Banks have been largely formed in this way, but there is no direct evidence of this, and a rough estimate of the quantities of material, the number of bergs, and the time required to form them makes it extremely improbable.

CHAPTER VI

UNDERGROUND WATER

The various agencies which have been described as operating upon the surface of the earth, that is, the atmosphere and the watery envelope of the globe in its varied forms of running water, the ocean, lakes, and snow and ice, all tend to cut away its irregularities and to furnish material which is used in filling up depressions. Hence they tend in the long course of time to make its surface smoother, and are therefore spoken of as *levelling* agencies. But water, in addition to this work of levelling, which is largely mechanical in its nature, performs other geological work of vast importance, and chiefly in a chemical way. One phase of this chemical work has been already discussed in connection with the formation of soil, page 23, and another has been alluded to in relation to that part of a river's burden which is carried in solution. But the matter as a whole is best understood through a discussion of the nature of ground-water and the functions it performs.

Ground-water. — It has been previously stated that of the water that falls in rain one part is evaporated and goes back into the air, that another portion passes directly over the surface into the sea, while a third portion sinks into the soil, and into the cracked and broken bed-rock below it. It is this last part of the rainfall, which thus sinks downward, that we know as *ground-water.* Various things may happen to it; it may find its way to the surface as springs and aid in the general run-off; it may be drawn to the surface by capillary attraction through the pores in the soil and be evaporated; it may be sucked up by plants and evaporated through their leaves; it may never return to the surface, but find its way into the sea by underground channels; it may remain held, for aught we may know, for indefinite periods in deep fissures in the rocks; and lastly it may enter into chemical combinations with the minerals of the rocks and become fixed. Before studying the geological side of these happenings certain features of ground-water should be explained.

Situation of Ground-water. — The water that percolates downward fills the fissures in the rocks and the interspaces, or pores, between the grains of overlying soil up to a certain level. Above

this level the soil may be moist, but the pores are not filled; below it the soil is saturated, consisting of a mixture of soil grains and water, like sand and water in a basin, and thus forming, so to speak, an underground lake. The surface, or upper level, of this ground-water is called the *water-table* and it is this water-table that one endeavors to reach and penetrate in ordinary dug wells. The depth of the water-table below the surface of the ground varies in a given locality in response to wet or dry seasons; in different localities according to circumstances, especially the annual rainfall. Thus in very humid regions it is generally but a few feet below the surface, while in very arid regions it may be hundreds of feet down, entirely below the soil, and in the rocks beneath. The depth to which ground-water may penetrate in the rocks is unknown, but experience in deep mines seems to show that it is not very far, and

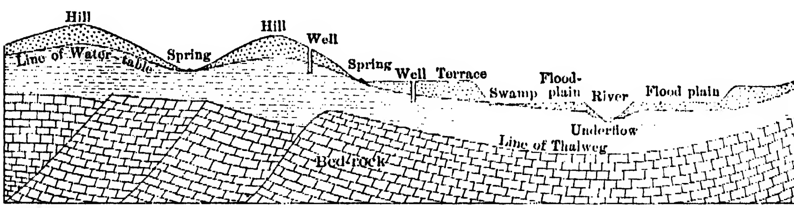


Fig. 125. — Ideal section across a river valley, showing position of ground-water, its relation to bed-rock below, and the contour of the water-table with reference to that of the ground above. Vertical scale exaggerated. After Slichter.

it must in any case cease at the point where, through the pressure of the superincumbent masses above, cracks and fissures in the underlying rock can no longer exist. This occurs, however, at a number of miles below the surface, since it has been demonstrated by Adams that cavities can remain open to a depth of at least 11 miles. Beyond this it may be that, in response to the pressure, all rocks, however rigid they may appear at the surface, are weaker than the pressure upon them and, yielding like metals under the stamping of a die, all cavities in them may be closed up.

Contour of the Water-table. — The contour of the water-table in a general way follows that of the ground above, rising under hills and sinking in valleys, as illustrated in Fig. 125. If the surface of the ground intercepts the water-table then the ground-water appears, and if this occurs on a hillside a spring results, while, if the surface of the ground and the water-table coincide for a distance, this area is a swamp or bog. In lakes and rivers the contour of the ground sinks below that of the water-table and the latter stands revealed.

Porosity of Soil and Rocks. — The volume of space between the grains of a soil, or its porosity, which can be occupied by water, depends very much on the nature and arrangement of the particles composing it. In ordinary sand the volume of pore space is usually about 30 per cent, and may be considerably larger; in ordinary loam, which contains a good deal of clay, see page 29, it may be still larger, from 40–50 per cent. Thus in a natural basin covering a certain area, in which the average depth of sandy soil is 30 feet to bed-rock, and in which the water-table stands 15 feet below the surface, the total volume of ground-water would equal that of a lake covering the area, and about 5 feet deep.

All rocks are in some degree porous, sandstone the most so, the volume of interspaces rising in some cases to 30 per cent in this rock, while in crystalline rocks, like granite for example, it may be only one per cent, or even less. This applies to the interspaces between the rock-grains and not, of course, to cracks or fissures, which can only contain a small part of ground-water. The average pore space is probably not over 10 per cent. Assuming this amount for the surface, and that it diminishes with the depth, it was formerly calculated that the total quantity of water held underground in the world was as much as one-sixth that contained in the ocean, but later investigations, which show the dry nature of the rocks in deep mines, have led to calculations which very greatly reduce this amount. In any case the total amount is actually very great.

Motions of Ground-water. — Probably only the lower depths of ground-water remain stationary for any length of time; that occupying the upper layers of rock and the soil has a slow but regular motion, depending on the difference of pressure due to gravity, from point to point. Thus it urges its way slowly onward from higher to lower levels and, ultimately, like the water of the run-off, it seeks its goal in the sea. In the sands filling a valley below the bed of a river, as illustrated in Fig. 125, the water underground is following the same course as that filling the channel above, though at a vastly slower rate. This is known as the *under-flow*. The rate of movement is relatively rapid in gravels and coarse sands, much slower through finer sands, while in fine clays it is almost indefinitely slow. A familiar example of this is seen in the rapidity with which puddles in a sandy road, after a shower, drain away, whereas in a bed of clay they remain until evaporated. Thus clay, and rocks composed of clay (shale), are practically impervious to the movement of water, while in sand and sandstone, on account of the porosity, it much more readily takes place. Yet even in sands the

movement is very slow, and a general average of the rate of underflow, as determined from experiments, is about one mile per year. The natural line of drainage over the underground surface of bedrock, along which the underflow takes place, may be called the *underground thalweg* (German, valley way), and is illustrated in Fig. 125.

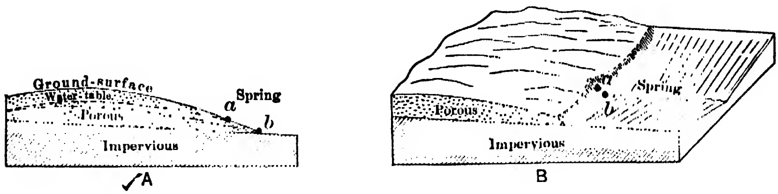


Fig. 126. — Diagrams illustrating conditions favorable for ordinary hillside springs. *A*, in section; *B* shows how the contour of the thalweg concentrates the seepage to form a spring. Dotted line, high-water stage, spring at *a*; solid line, low-water stage and spring at *b*.

Fig. 127. — Thousand Springs, Snake River canyon, Idaho. I. C. Russell, U. S. Geol. Surv.

Springs. — Where the contour of the ground intercepts the water-table, ground-water appears at the surface. A general oozing out of the water under these conditions is known as *seepage*, but if the circumstances are such that a volume of the water issues out in quantity sufficient to form a distinct current, an ordinary spring results, as illustrated in Fig. 126, *A* and *B*. Fig. 127 illustrates the cutting of the water-table by the side of a canyon, and the issuance of the underground water in a series of springs.

Another type of spring is formed when the surface water enters and fills some porous, inclined layer, such as one of sand, or sandstone, lying between two impervious ones, as of clay or shale. Driven onward by the weight of the column behind it the water may ac-

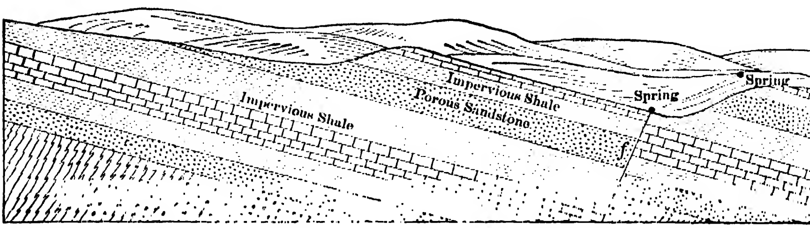


Fig. 128. — Section illustrating conditions favorable for springs, if fissures, such as *f*, are present, or for artesian wells if fissures are absent.

quire such hydrostatic pressure that, if it encounters the plane of a fissure, it may be driven up along this, through suitable channel-ways, and issue at the surface as a spring. This is illustrated in Fig. 128. Such springs are often called *fissure springs.*

In such an arrangement as is postulated in the figure, along the line of intersection of the fissure with the surface, springs might be expected at various points where suitable channels for the upward flow of the water exist, as suggested in the diagram.

Such springs are usually very steady in their flow, and less liable to be affected by droughts than ordinary hillside springs. While usually cold, the water may come in contact with heated rocks and issue in a warm spring. This is probably the explanation of the warm springs occurring at various places in the Appalachians, as at Hot Springs, Virginia. Or the water may sometimes take up substances in solution and give rise to *mineral springs,* as at Saratoga, New York.

The condition under which porous beds become filled with water is important, not only for fissure springs, but also for artesian wells, described below. It is illustrated in Fig. 129. The porous layers *BD* become filled, not alone by the rain which may chance to fall on their exposed surfaces, and by the water which is shed upon them from the higher impervious slopes *A* and *C*, but there is also an entrance of water into them from the current of the river, concentrated from the water-shed above and beyond, which, spreading out in them, furnishes a constant source of supply.

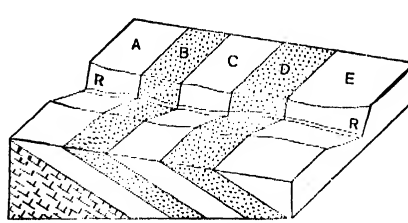


Fig. 129. — Diagram to illustrate entrance of water into porous rock layers, or strata. *ACE*, impervious beds; *BD*, porous ones. *RR*, course of river.

Artesian Wells. — If under the conditions described above as producing fissure springs, where an inclined porous rock-bed between impervious ones becomes filled with water under sufficient pressure, a bore hole be put down, the water will rise to the surface, producing an *artesian well.* This may be regarded as an artificial fissure spring, and the arrangement illustrated in Fig. 131 is especially suitable for such wells. In some cases the porous layer may have underground the form of a basin, but this is not a

Fig. 130. — Artesian well, near Provo, Utah. G. E. Richardson, U. S. Geol. Surv.

necessary condition. The height to which the water will rise above the surface depends on the pressure, which in turn depends on the height of the water column, or "head," in the porous layer above the point of exit, as shown in the figure. An artesian well is shown in Fig. 130.

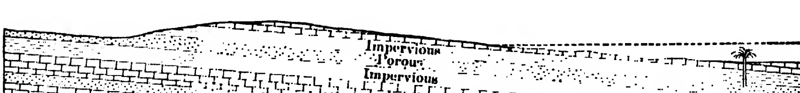


Fig. 131. — Section showing conditions favorable for an artesian well. Vertical scale exaggerated.

The terms porous and impervious used in this connection are relative ones, as all rock-beds are to some extent porous. In addition to the conditions men-

tioned as necessary for artesian wells, others are that there should be a rainfall over the region where the porous layer comes to the surface sufficient to keep it filled with water, and also that the rock-beds should not be so cracked, fissured, or displaced as to permit the easy escape of the water and thus cause the loss of the required pressure. Artesian wells cannot, therefore, be made in any place by simply boring deeply enough, unless the requisite geologic conditions are present. Any well bored in rock, if it simply intercepts the level of ground-water, is often called an artesian well, but this is an incorrect use of the term; there is no difference in principle between one of this kind and an ordinary dug well. Some of the most important water-bearing formations in the United States, which furnish artesian wells, are found in the so-called Dakota sandstone, which comes to the surface along the Rocky Mountains, and underlies North and South Dakota, Kansas, Nebraska, and extends into Canada; in the Saint Peter sandstone, which outcrops in central Wisconsin, and underlies Illinois, Indiana, Iowa, and Ohio; and in the beds of sands and clays, which, beginning on Long Island, extend southward to Texas, forming the Atlantic coastal plain. In New England the conditions are unfavorable for artesian wells.

The depth to which wells must be bored in some places before artesian water is attained is very great, up to 4000 feet, examples being found in Berlin, St. Louis, and Pittsburgh; those of 1000 feet are not uncommon, while along the Atlantic coast they are generally shallow, 100—300 feet. The volume of water may be very large, the great 12-inch well at St. Augustine, Florida, with a depth of 1400 feet, supplying 10,000,000 gallons a day. Where many wells are put down close together they may interfere with each other, and even lower the pressure to such an extent that the water will no longer overflow.

Geologic Work of Ground-water

Water underground is a very important geologic agent. The chief work that it does is to *take substances into solution and carry them elsewhere, often finally depositing them*, and it is, therefore, chemical in its nature. Although this work may seem small, when examined in detail, the total results performed during the long period of geologic time have been enormous. In some measure this work has already been considered. Thus in the description of the decay of rocks and the formation of soil it was pointed out that certain constituents, like the alkalies in the feldspars in the rocks, went into solution and were removed. It was also shown that calcium carbonate, a common rock-making material, under the influence of water and carbon dioxide was dissolved and carried away (page 25). These actions are accomplished by atmospheric water as it passes underground, and may thus be regarded as the first stages of the work of ground-water. Again its work was in some degree considered, when it was stated what a large proportion of the burden carried by rivers consisted of material in solution (page 45).

This shows the removal of the substances dissolved by ground-water and their ultimate goal in the sea. And again in the formation of salt lakes, and in the deposits which occur in them (page 84), is seen this work of solution, removal, and deposit.

But although all these illustrate the general chemical work of water, partly on the surface and partly underground, there are certain features which demand particular consideration.

Solution. — The solvent action of rain-water passing into the soil and rocks is greatly increased by the substances which it may carry

Fig. 132. — Rock whose more soluble parts are being dissolved by the action of atmospheric waters. Wind aids the rain in removing the loosened material. Near Livingston, Mont. C. D. Walcott, U. S. Geol. Surv.

with it, or which it may otherwise obtain. In its passage through the air it dissolves notable quantities of carbon dioxide and oxygen, with minute amounts of other materials, and is thus equipped for doing chemical work. See Fig. 132. In passing through the soil of humid regions it may absorb much more carbon dioxide, and also organic acids produced by the decomposition of vegetable matter. In many places, particularly volcanic regions, volatile substances, especially carbon dioxide, are evolved from the depths, and may dissolve in the water underground and thus greatly augment the amount of chemical reagents present in it. All of these promote its efficiency as a solvent. In addition, as it passes into deeper zones,

it may become subject to pressure, or come in contact with heated rocks and have its temperature raised, both of which largely increase its chemical activity; the amount of gases, such as carbon dioxide, which it can dissolve and hold in solution, is, indeed, proportional to the pressure.

Pure water itself acts upon many things, but with its chemical efficiency heightened as just described, it attacks the mineral substances composing the rocks and soils; some of them it takes directly into solution, as, for example, gypsum, $CaSO_4 \cdot 2H_2O$; with many others a chemical reaction takes place with formation of new compounds, some of which are soluble and are carried away, while the insoluble ones remain. This latter process is illustrated in the breaking up and decay of feldspar, as described under the formation of soil; the alkaline carbonates produced are leached out, whereas the insoluble kaolin, or clay, remains.

One sees, therefore, from this that the outer portion of the earth's crust, over the land surfaces, is one of destruction and change. And this is not limited to the merely superficial layer, in which the rocks are changed into soil, but extends downward into the zone of cracked and fissured rock far below.

The material taken up and held in solution may pursue one of two courses, depending on what happens to the water containing it. It may work down deeply into the rocks and be there deposited, or it may pass into the drainage by leaching through the soil, or by coming out in springs, and be thus carried into the ocean. The first course may be considered a little later, we are here concerned with the material taken away.

Chemical Denudation. — The process by which the land surface is wasted by material going into solution and being taken into the sea is known as *chemical denudation,* to distinguish it from the mechanical wear of ordinary erosion. In the aggregate it amounts to an enormous sum each year. It has already been briefly mentioned in the discussion of a river's burden. On the basis of a large number of analyses of the waters of the Mississippi, which give the average percentage of the salts which it contains, and of the total volume of its discharge, Dole and Stabler have calculated that each year there are removed 108 tons (metric) of matter in solution per square mile over its basin. This does not mean, of course, that this amount is taken from each square mile, but is the general average; it is more in some places, in others, less. If we estimate the area of the basin in round numbers at 1,265,000 square miles this gives 136,620,000 tons per annum for the total basin. For the

entire United States (3,088,500 square miles) — regarding denudation of the Great Basin as not adding to the ocean — the average is estimated at nearly 79 metric tons per square mile. This figure has been used by F. W. Clarke as a fair average for the whole of North America, and gives 474,000,000 tons for its total area. For the whole world this estimate of 79 tons would be too high, for arid desert regions, like those of central Asia and Africa, have a scanty drainage, and thus lose a relatively much smaller amount of mineral matter in solution. The same is true in humid tropical countries where the soil, held in place by dense vegetation, has for centuries past been leached of its soluble matter, and in Arctic regions where the drainage is largely over frozen soils which contribute very little. Taking these facts, as well as others, into consideration, Clarke estimates that the average is about 68.4 tons per square mile for the land surface of the world, leaving out the polar areas which have little or no water drainage; or a total of 2,735,000,000 tons per year. Making certain corrections we may deduce from this that the land surface of the globe, which is subject to the solvent action of water, is lowered on the average by this agency one foot in 30,000 years.

Results of Solution on Carbonate Rocks. — Outside of the process of soil formation, in which solution also plays an important part, the most obvious results of its action are seen in the effects it has upon rocks wholly, or partly, composed of carbonates. The most important rock-forming carbonates are those of calcium, magnesium, and ferrous iron; $CaCO_3$, $MgCO_3$, and $FeCO_3$. Of these the first two, and especially the carbonate of lime, are the most important; vast stretches of the land being covered with beds of rock, hundreds or even thousands of feet thick, which are composed of them. Such rocks, if they consist wholly, or mainly, of carbonate of lime, are called limestone; if they contain much carbonate of magnesia, dolomite. In addition, beds of sandstone, excepting most of those that are red or brown, may contain a cement of carbonate of lime holding together the grains of sand. Now since these carbonates, and especially lime carbonate, are attacked by water containing carbon dioxide in solution, as has been previously explained (page 25), with formation of soluble bicarbonates, it is obvious that under the action of atmospheric water, which always contains this gas to a greater or lesser extent, such rock masses as those mentioned must be continually dissolving and wasting away. This is shown in the fact that in those places where limestone, or calcareous sandstone, is the bed-rock the water is always *hard,* i. e., contains

lime in solution, as proved by the deposit formed in tea-kettles. This work is most strikingly illustrated in the formation of sink-holes and caverns, which result from underground drainage.

Sink-holes and Caverns. — In regions where limestones form the bed-rock the surface waters working down through joints and fis-

Fig. 133. — Sink-hole in limestone beds; near Cambria, Wyo. N. H. Darton, U. S. Geol. Surv.

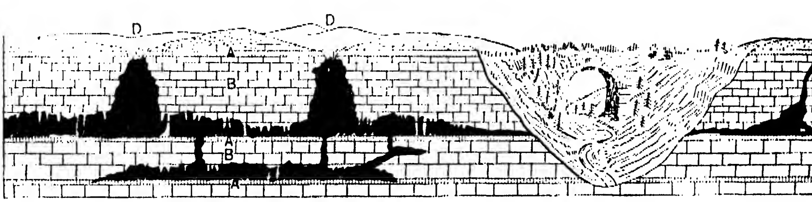


Fig. 134. — Diagram illustrating the formation of caverns and sink-holes in limestones. *A A*, clay beds; *B B*, limestones. The arch is the remnant of the roof of a former cave, forming a natural bridge. *D D*, sinks, leading to domes below. Modified from Shaler.

sures may enlarge these by solution. Coming to an insoluble layer, such as one of clay or shale, they are stopped in their descent and spread laterally, finding their way through the rock fissures along the natural drainage slope. These fissures are also enlarged by solution until they become distinct water channels. As the latter enlarge they form *caverns*, while the holes or pipes, leading down to them from the surface above, are termed *sink-holes*. The process is illustrated in Figs. 133 and 134.

The cavern domes hollowed out in the rock are sometimes 100 feet high, or more, and several hundred feet broad. They are connected by intricate passages. The floor on the insoluble stratum may be quite level for long distances. Breaking through this layer, the waters excavate new passages and chambers at a lower level, as illustrated in the diagram, Fig. 134, until there may be several sets of such rooms and galleries, one above the other.

The limestone regions of the middle West and South are noted for their caverns, some of the best known being Mammoth Cave in Kentucky, 10 miles long or more, with 30 miles of winding passages; Wyandotte Cave in Indiana, Luray Cavern in Virginia, and many others. In some places the rocks are almost honeycombed with them.

Fig. 135. — Silver Spring, Florida. G. I. Adams, U. S. Geol. Surv.

It may happen in such regions that almost the entire drainage passes underground. Large rivers disappear from sight and, after a devious journey below, may come to the surface again in a different drainage area. In thus issuing they may give rise to huge springs, thus Silver Spring in Florida has an overflow so large that the resulting stream is navigable for small steamers, see Fig. 135. In other cases they may boil up as great springs in the sea, not far from land.

In addition to the caverns described above, limestones, where they are exposed to the weather, commonly show pitted, hollowed, or cavernous surfaces, owing to the solvent activity of water. The same is true of calcareous sandstones, those with a cement of carbonate of lime; the latter dissolving, the sand grains fall apart and are washed or blown away. Many strange and often weirdly shaped masses of rock are left as remnants through this combined chemical and mechanical erosion, see Fig. 132.

Deposition and Cementation. — From what has been previously stated it is clear that there is an upper belt in the earth's crust where mechanical and chemical changes and destruction are going

on. It is known as the *zone of weathering,* and extends downward to the level of ground-water. From this zone, material is being constantly leached out and carried downward in solution into the ground-water. This matter is either carried away by the drainage, or it may be deposited in pores, fissures, and cavities in the rocks. The lower limit to which this can extend is uncertain, and appears to depend on several conditions, and it probably varies in different places. Thus the intervention of non-porous rock-layers, or the charging of the rock-pores with gas under pressure, would hinder, or perhaps prevent, further downward movement in a given area. In this belt, whatever its thickness may be, the rocks are being solidified and cemented by the silica (quartz), carbonate of lime (calcite),

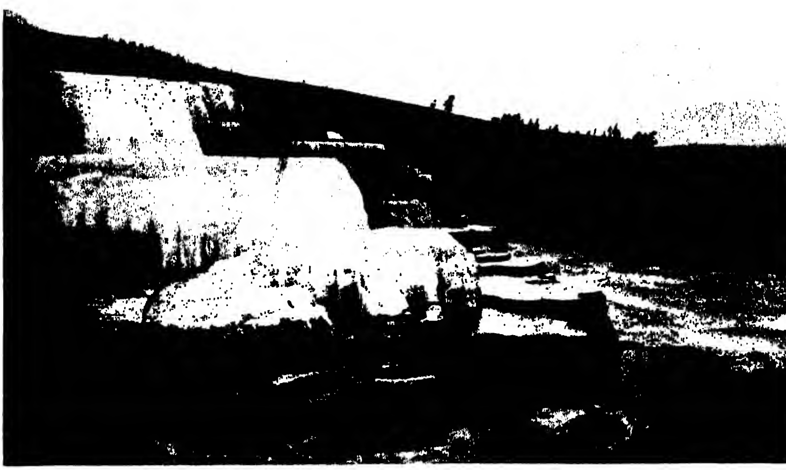


Fig. 136. — One of the terrace formations of the Mammoth Hotsprings, Yellowstone Park, Wyo.

and other substances deposited in them, and it is, therefore, known as the *zone of cementation.* A proper appreciation of this process and its results is of great importance, for by it we are able to understand the significance of certain geological features which will be considered later.

Deposits of Carbonate of Lime by Springs. — The material in solution, which is not deposited in the rocks, is carried away by the drainage. Sometimes it happens that on its way to the sea it again comes to the surface, and is temporarily deposited. This is best illustrated in the case of springs which deposit carbonate of lime.

Many springs, and especially deep or fissure ones, contain carbon dioxide gas, often in quantity and under considerable pressure, and thus when the water passes through beds of limestone on its upward way large quantities of lime carbonate are taken into solution, the amount depending on that of the gas under pressure. On arriving at the surface, partly through evaporation and partly by loss of gas through the relief of pressure, the lime carbonate is deposited, and in this way mounds and formations may be built up, which often display striking features, and are of great beauty. They are illustrated in the basins and terraces of the Mammoth Hotsprings in the Yellowstone Park, Fig. 136.

In some springs, especially deep ones, the issuing water may be warm, or even hot. This is apt to be the case when they occur in regions of active or recently extinct volcanic activity, like that in which the Mammoth Hotsprings are situated. In warm waters the deposit of lime carbonate may be much increased by the action of low forms of vegetable life, algæ, living in them which secrete this substance from the water. It is probable that the warmth and chemical activity of the waters of some springs, particularly hot ones in volcanic regions, are greatly increased by gases and vapors coming from molten or heated rock masses lying in the depths below. As water is believed to be the most considerable of these, the volume of water discharged may be increased by this agency.

In many cases the deposit takes place so rapidly that articles suspended in the spring become covered in a few days with a coating of carbonate of lime.

Other examples of such springs are found in Virginia, Colorado, Banff in Alberta, Karlsbad in Bohemia, Tuscany, and in many other places. In addition to carbonate of lime, spring waters often contain other mineral substances in solution, sometimes entirely replacing it, and such mineral springs are often used medicinally, as at Saratoga and other health resorts.

Deposits in Caves. — The same process which forms caverns also tends to fill them up. For, after they have been made by underground drainage in the manner described above, the surface waters seeping down through the rock-beds which form their roofs dissolve more carbonate of lime, and deposit it in them, producing stalactites and stalagmites, columns, pillars, etc. The manner of their formation is as follows: A drop of water, charged with lime, leaking through to the roof hangs there for a time. While resting it evaporates somewhat, and also loses some carbon dioxide, and, consequently, deposits some lime carbonate. Finally, as it gathers volume, it drops, and falling on the floor below it repeats the process, leaving another deposit. Thus there gradually grow downward from the roof long pendant incrustations, like icicles, which are called *stalactites*, while the rising deposits on the floor are known as *stalagmites*. Finally, these may increase so that they unite and

produce columns. They are especially liable to form along lines of fissure in the roof. See Fig. 137.

In this way formations of great beauty, and often exhibiting many strange and curious forms, have been produced. In past times caves have served as refuges for primitive men, who inhabited them, or as dens for wild animals. Through this the bones of men and animals, stone implements, and other objects have accumulated in them and been sealed up, like fossils, in the deposits of carbonate of lime on their floors, to reveal to us, when broken open and explored, much concerning the life and degree of culture existing in prehistoric times.

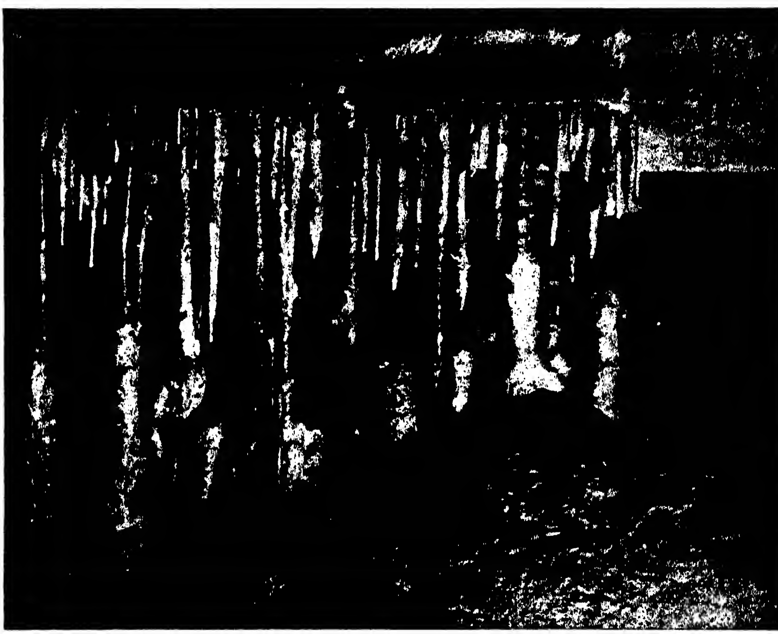


Fig. 137. — Stalactites, passing below into stalagmites, along a roof-crack. Marengo Cave, Indiana. G. P. Merrill, U. S. Nat. Mus.

Nature of Lime Deposits; Travertine, Tufa. — The character of the material formed when carbonate of lime is deposited from solution depends on circumstances, and especially on the rate of deposition. When produced by slow evaporation, as in the stalactites in caves, it is a hard, compact, more or less crystalline substance. A general name for deposits of carbonate of lime from solution is *travertine*, from the old Roman name of a town (Tivoli) in Italy where an extensive formation of the substance exists. The so-called Mexican "onyx" or "onyx marble" is a travertine with banded

structure brought out by varied tinting from metallic oxides. But when formed rapidly from springs, the travertine may be porous or loose, or coating vegetation it may be spongy or mosslike, and such less compact varieties are commonly called *calcareous tufa,* or sometimes *calcareous sinter.* Great deposits of this are also found around the shores of dried-up alkaline lakes, such as Pyramid Lake in Nevada, encrusting the rocks of the enclosing basin, as mentioned on page 86.

It should be clearly borne in mind that these deposits are not *original* formations of carbonate of lime, in the sense in which we

Fig. 138. — Alkali flat, Malheur Lake, Oregon. I. C. Russell, U. S. Geol. Surv.

might think of that word in connection with limestone; they represent, certainly for much the greatest part, previously existent carbonate of lime, such as limestone, chalk, etc., which has gone into solution, been transferred to another place, and deposited. They merely exhibit a temporary stoppage of the material on its way to the sea, for it is the fate of all deposits of carbonates, exposed to atmospheric agencies, to be dissolved and taken into the ocean. Some have even had the view that thick formations of limestone, covering wide areas, have thus dwindled and disappeared, but this idea may be carried too far. What happens to the carbonates in the sea, and how the limestones, which furnish the secondary deposits of travertine and tufa, were made we shall see in a later place.

Other Deposits by Springs; Iron Oxides, Silica, etc. — Substances other than travertine may be deposited when underground waters issue at the surface. One of these is the hydrated oxide of iron, or, under certain circumstances, iron carbonate. This is a matter of importance because, as is commonly supposed, extensive

beds of valuable ore have been thus formed. Also silica, sulphur, and gypsum may be deposited, but since agencies other than those which have thus far been described, are also, as a general thing, concerned in the process it is better to wait until these latter have been considered before discussing them.

Alkali Deposits. — In humid regions the soluble substances that are formed in the decay of the rocks are quickly washed out of the soil, and passing into the drainage are carried into the sea. In arid and desert regions where the rainfall is scanty there may not be sufficient water to perform this function. The salts remain in the soil, at times of rainfall they go into solution, and in the subsequent times of dryness, when the water draws to the surface, on its evaporation they are left, forming the white incrustation on the soil known as *alkali,* a common feature in many parts of our western regions, see Fig. 138.

The common salts in the so-called alkali are sodium sulphate, sodium chloride, and sodium carbonate, Na_2SO_4, $NaCl$, and Na_2CO_3; it is to the alkaline reaction and taste of the latter that the name is due. Magnesium sulphate, $MgSO_4$, and sulphate of lime, or gypsum, $CaSO_4 \cdot 2H_2O$, are often present. These salts are not always formed by rock decay; they may have been originally present in the rocks, if these are composed of beds of sediments laid down in the sea. Their concentration in such arid regions, with inland drainages, gives rise to salt and alkaline lakes. See page 86. The irrigation of alkali lands, especially if the water is too freely or carelessly used, may bring the salts to the surface in such quantities as to injure, or even ruin them for agriculture.

Mechanical Work of Water Underground; Landslides. — As a mechanical agent underground water must play a small geological rôle. It is conceivable that streams running in subterranean channels may at times both erode and transport, but the circumstances which would permit this must be exceptional. A more important function is its aid in causing landslides, both in helping to overcome the friction of masses of rock, earth, and débris lying on steep slopes, and in adding weight to such masses. In producing such results it is often powerfully aided by the action of frost, as mentioned on page 21. The masses of earth and rock when saturated with water act like a semi-fluid substance and, started from their insecure foundations at times of extraordinarily heavy rainfall or by earthquake shock, rush down into the valleys below, often causing great damage and considerable changes of topography. In high mountainous regions such landslides, due to these causes and shattered condition of the rock masses, may precipitate huge trains of broken

rock, or talus heapings, for long distances downward, giving rise to rock streams. The onward motion of trains of talus, or "rock glaciers," as they have been sometimes called, due to freezing and thawing, and to gravitational creep, has been already stated on page 118.

CHAPTER VII

ORGANIC LIFE AND ITS GEOLOGICAL WORK

Over the greater part of the land surfaces and in the sea, life, both animal and vegetable in varied forms, is present and, quickened by the energy imparted by heat and light from the sun, is causing movement of material on the earth's surface and transformations of matter by chemical changes. Compared with the vast bulk of the globe such actions, and their results, appear relatively superficial and small; from the human standpoint, however, they are not only great, but of far-reaching importance and worthy of careful consideration.

Organisms work in various ways: in some cases they tend to break down existing structures and their action is thus *destructive;* in others they build new ones and their work is therefore *constructive.* Sometimes they preserve existent structures from the destroying action of other agencies, and thus are *protective.* The most important protective effect is the influence of vegetation in restraining the erosion of the soil, a matter which has already been sufficiently treated (page 33) under erosion.

Destructive Work of Organisms

Destructive Work of Plant Life.—The most important geological process which plant life carries on in growing is to decompose the carbon dioxide gas in the atmosphere, storing up the carbon and returning to it the oxygen. This produces several important effects which will be considered in their proper places. On their death and decay the carbon of the vegetable tissues of the plants may be largely, or even wholly, reoxidized to carbon dioxide, and this being taken into solution by the descending surface waters forms carbonic acid, which, as we have already seen in several places, is a solvent of rock material.

The carbonaceous residue from the decay of vegetation existing in the soil, which it colors dark, or black, is known as *humus.* In the production of humus, not only carbonic acid, but other compounds are formed, some of which are organic acids called humic, ulmic, etc. These also attack the rocks and help to convert them

into soil. Even the roots of growing plants secrete carbon dioxide and contain organic acids, such as citric acid, which exert a solvent influence on the minerals composing the rocks. Thus in its life, death, and decay, vegetation is exerting a constant chemical effect upon the soil and rocks, changing the existing substances into new ones, many of which are soluble and carried away by the circulating waters. This is most strikingly seen in its effect upon the *oxides of iron* which color the soils red or yellow. They consist of *ferric oxide*, Fe_2O_3, usually more or less hydrated, as in limonite, $2\ Fe_2O_3.H_2O$, which makes yellow ocher when mixed with clay. Decay of organic substance is a process of oxidation; mostly the oxygen is taken from the air, but if the organic material is in contact with ferric oxide it will also take oxygen from it, reducing it to *ferrous oxide*, FeO. The ferrous oxide, however, as it forms, unites with the carbon dioxide, also being produced, and makes *ferrous carbonate*, $FeCO_3$. The process may be reduced to simple chemical equations by considering the organic substances, which really consist of carbon, hydrogen and oxygen, as if composed of pure carbon, as follows:

$$2\ Fe_2O_3 + C = 4\ FeO + CO_2, \text{ and } FeO + CO_2 = FeCO_3.$$

The ferrous carbonate, like calcium carbonate, is soluble in water containing carbon dioxide, and as this is always present to a greater or lesser extent, the iron compound is taken into solution, leached out and carried away. Thus while *ferric oxide*, so common a coloring material and cement in rocks and soils, is insoluble in meteoric waters, by the aid of organic matter it is converted into the soluble *ferrous carbonate*, dissolved and removed. What becomes of it we shall consider later.

Certain features regarding the coloring of rocks and soils are explained by this process. Thus the soil lying below a covering of vegetable mold (humus) is usually decolorized and, therefore, of light hue, or white, because the solutions of organic matter leaching downward from above have changed the iron oxide and removed it. This may be often observed on the sides of banks, railway cuttings, and excavations.

On the other hand, a clay which contains much organic matter is dark in color, dark-blue, dark-gray, or greenish to black. In such clay, iron, if present, is in ferrous compounds on account of the reducing action of the organic substances and, as ferrous compounds have little or no coloring effect, the coloration is due to the dark carbonaceous material. When these clays are fired, however, the organic matter is burned out, the iron oxidized to the ferric condition, and red brick formed.

In desert or very arid regions the cliffs and rocks are often strongly colored red, or less often yellow, because of the oxidization of the iron compounds in them and the lack of vegetation in such places, whose decay would reduce the ferric compounds and decolorize them. Thus vivid color tones are often

characteristic of many arid landscapes. The prevailing color of sandy deserts is, however, gray, often pale yellow, less often red.

With regard to the soils it may be said, in general, that while a red color is characteristic of many of the residual soils of to-day in warm moist climates, in ancient deposits, now hardened into rock, it is apt to be associated with salt and gypsum, which, as will be shown later, are indicative of arid conditions.

The importance of the principles here laid down will be seen later, when the climates of past times in different places, and their significance, are treated, and the formation of beds of iron-ore is discussed.

Fig. 139. — Rock split by a tree growing from a seed which lodged in a crack. Sierra Nevada, Cal. G. K. Gilbert, U. S. Geol. Surv.

In addition to the chemical work of plant life just described, vegetation also acts in a *mechanical* way to destroy existent structures. The most important part of this work is seen in the splitting and disintegration of rocks by the roots of trees, shrubs, and other plants. They insinuate themselves when minute into crevices and, expanding as they grow, they exert a disruptive force which even solid masses of rock are unable to withstand. Instances of this in exposed ledges and bowlders, where seeds have lodged in cracks, and have germinated and grown, enlarging the cracks and disrupting the rock, are everywhere common. Such a case is illustrated in Fig. 139. In the course of long ages the amount of work done in this

way, especially on rocks in the soil, must be very great, and the general action of weathering facilitated by the preliminary effect of roots.

Destructive Work of Animals. — Animals are much less destructive agents than plants yet on the whole they accomplish considerable geological work. It is done chiefly by those kinds which live and move about in the soil, such as worms, ants, moles, gophers, etc. By making holes and burrows, and upturning the soil they expose fresh surfaces to weathering and erosion, or by opening it up they facilitate the entrance of the weathering agents to lower levels. Thus Darwin states as the result of his investigations that in England the earthworms bring to the surface 10 tons of mold to the acre every year, while Branner believes that in many tropical regions the ants are even more effective in upturning the soil.

The most destructive animal in regions populated by him is Man, and this is due to the fact that over such wide areas he has felled the forests, and otherwise destroyed the natural vegetal covering of the soil, in order to cultivate it, thus throwing it open to attack by the agencies of erosion. This has already been discussed under erosion, page 33. The work of man as a geological agent is also seen in the diversion of drainages he has effected by wells, canals, dams, piers, dredgings, etc., although all of this is by no means destructive in its nature. The extermination of animals and plants, and the introduction of new species of both, in the settlement of new countries by man, is also a process which has a geological bearing, and has been going on at an increasing rate for an immense period of time, since man first definitely assumed his position as master of living organisms.

There should be mentioned here also the chemical changes wrought by the decay of dead organisms in the sea, much of which is destructive in character. Both plants and animals contribute to these changes, which take place chiefly on the bottom. The decomposing organic matter reduces the sulphates in sea water to sulphides, with consequent formation of sulphuretted hydrogen, H_2S, which may precipitate sulphides, such as pyrite, FeS_2, or be oxidized to sulphuric acid, H_2SO_4. The acid may attack the lime carbonate in shells, and convert it into gypsum, $CaSO_4 \cdot 2H_2O$. This may serve as an example of chemical changes going on in the sea through the agencies of organic life. Carbonates, sulphates and phosphates are the chief results. *Diagenesis* is a general term for these processes, which are of great importance in various ways, as we shall see later when we shall have occasion to refer to them.

Constructive Work of Organisms

Constructive Work of Plants. — The manner in which plant life acts as a constructive geological agent is best seen in the formation of peat and its conversion of lakes into bogs and swamps. This has been briefly mentioned in the life history of lakes, page 82, and may now be more fully considered. We will commence by learning what peat is, and how it is formed.

Peat. — It has been previously stated that growing plants decompose the carbon dioxide of the atmosphere, using the carbon and largely returning to it the oxygen. In addition they demand water, which consists of oxygen and hydrogen, and certain mineral compounds furnished them by the soil. Their tissues, therefore, consist chiefly of carbon, hydrogen, and oxygen, but contain mineral substances, and in some cases nitrogen also in small amount. Disregarding the minor constituents, the chief substance composing their frame-work is *cellulose*, $C_6H_{10}O_5$, which, for the sake of simplicity in this connection, we may regard as forming the organic matter of plant life.

If dried organic matter, or cellulose, be burned with free access of air, a complete process of oxidation takes place, with formation of carbon dioxide and water vapor, as follows:

$$C_6H_{10}O_5 + 12\,O = 6\,CO_2 + 5\,H_2O.$$

If the heating, or burning, is conducted without access of air, or of but a limited amount, as when wood is charred in a kiln, or with earth thrown over it, the oxidation is incomplete, the hydrogen, oxygen and some of the carbon are removed, partly as above, but the greater part of the carbon remains as charcoal. Somewhat similar processes take place in nature when organic matter decays. Decay is caused by the growth and action of bacteria, minute organisms, and is a process of oxidation. If it takes place in the open air, as when leaves fall upon the ground, it may be in time complete, and the cellulose returned to the atmosphere as carbon dioxide and water vapor, as if it had been burned.

On the other hand, if the organic matter decays where the access of air is prevented, as when plants grow in water, or their leaves, twigs, stems, etc., in falling pass beneath its surface, a process somewhat analogous to the formation of charcoal takes place. The oxidation is only partial, some of the hydrogen being removed as water, H_2O, some of the carbon as carbon dioxide, CO_2, and some of both as marsh gas, CH_4. The resulting product of partly decayed organic matter is much richer in carbon and poorer in hydrogen than

the original material, and is known as peat. *Peat* is, ~~therefore~~, the brown to black carbonaceous matter formed by the partial decay of vegetable matter in the presence of water.

The reason for the arrest of decay in this case appears to be that the bacteria producing it evolve waste products, which, if not removed, are unfavorable to their continued growth and existence, that is, they are antiseptic in nature. When the condition is reached that the water saturating the decaying organic matter is changed to a sufficiently strong antiseptic solution from the presence of these substances, the bacteria can no longer exist, further decay is prevented, and the peat formed is preserved.

Formation of Peat and Lake Filling; Bogs. — Although peat is formed to some extent in warm and even tropical regions, it is es-

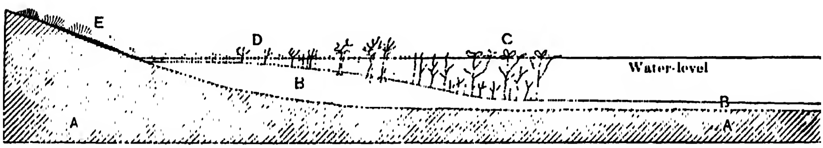


Fig. 140. — *A*, bed-rock of lake basin; *B*, accumulating layer of peat; *C*, aquatic vegetation, pond-lilies, water-weeds, etc.; *D*, bushes and semi-aquatic plants, mosses, etc.; *E*, climbing bog. Modified from Shaler.

pecially in temperate and cold humid countries that it is produced. Some of the various circumstances under which this happens, and their results, are discussed in the following paragraphs. Thus, where lakes abound, especially in humid regions, constant formation of peat in shallow water is going on, and is slowly but steadily filling them up. In the water are growing various kinds of aquatic vegetation, pond-lilies, water-weeds, rushes, etc. When these die their leaves, stems, and roots at the bottom form a black mud composed of peat. As these masses of vegetation, and the deposits they leave behind them, advance lakeward, bushes and semi-aquatic plants, such as certain mosses, appear in the shallowing water, and close to the shore, and add their quota to the peat deposits below. This is illustrated in the diagram, Fig. 140.

Eventually there comes a time when the peat formation reaches to the top, or nearly so, the basin is filled with the soft black mud which forms the final stage of the peat, the lake is obliterated and a *bog* formed in its place. See Fig. 141.

This process is especially important in small lakes and ponds, and in the shallow bays and lagoons formed by bars or barriers in large lakes, where the depth is not too great for plant life to gain a foothold. In the larger and deeper lakes it may be at first a relatively unimportant factor in filling, com-

pared with the deposits produced by incoming sediments, but when the stage is reached where vegetation becomes abundant this may be reversed.

In northern regions the plants most efficient in forming peat are species of mosses, especially *sphagnum* (bog-moss), sedges, and certain flowering plants which grow rapidly, producing a spongy, cushion-like layer saturated with water. While growing above, the stems die below, making the peat. As indicated in Fig. 140 the plants tend to grow in definite zones; first the floating lilies, next shoreward the sedges, rushes, etc., followed by mosses, land

Fig. 141. — Lake filling; final stage where it is turned into a bog by accumulated peat. Near Hammond, La.

bushes, and, finally, very often swamp-loving trees, larches and spruces, near the edge. Where suitable conditions exist, especially in small lakes, the vegetation pushing outward from the shore may form a floating mat. Eventually when the lake is filled by the deposited peat the bog-moss and bushes form a cover concealing the black and treacherous quagmire below. Especially in the many small, shallow lakes of glacial origin in northern countries is this filling going on. Over wide regions, as in Newfoundland, Labrador, etc., not only the surface of filled lakes, or bogs, but all shallow depressions and in some places the level ground, hill-slopes and hill-tops, even isolated rocks, are covered with this saturated layer, giving a bog-like aspect to the entire country. In sub-arctic regions, as in Alaska and Siberia, the country covered by this wet, mossy mantle of bog, which may be even continually frozen a small depth below, is known as *tundra*.

Southern Swamps. — In temperate to tropical regions the mossy bogs of the north are replaced by swamps filled with trees, bushes, canes, vines, etc., whose decay forms the peat. Such are the swamps along the lower Mississippi and its tributaries, the Great Dismal

Swamp in Virginia and North Carolina, and the marshes and swamps of Florida. Dismal Swamp covers an area 30 miles long by 10 broad, and appears to have been caused by the obstruction to drainage produced by accumulations of dense vegetation on a plain lying near sea-level. The trees covering it, of which the cypress is the most characteristic of this and other southern swamps, maintain themselves in the soft peat mud by platforms of wide spreading

Fig. 142. — Dismal Swamp, Va. The projections from the cypress roots serve to give them air; they extend downward into the mud and help to anchor the tree in the semi-liquid mass of the bog. I. C. Russell, U. S. Geol. Surv.

roots. In the swamp is Lake Drummond, six miles in diameter, but very shallow, its banks and bottom composed of pure peat. A view in this swamp is seen in Fig. 142. In tropical regions, as in the basins of the Amazon and Nile rivers, vast swamps and marshes occur, formed by the obstruction to drainage caused by the rapid growth and accumulation of vegetation on an enormous scale, especially of aquatic kinds, such as rushes, canes, etc. These also give rise to peat deposits.

Marine Marshes. — In bays and harbors along sea-coasts and on the deltas of large rivers vegetation plays a prominent part in helping to turn shallow-water areas into marine marshes. For when the depth of water is sufficiently small, or becomes so through de-

posit of sediment, marine vegetation, partly growing completely submerged, or aquatic, like eel-grass, partly semi-aquatic, like certain grasses and rushes, takes root and flourishes. At high tide this band of vegetation may be well covered with water, but, as the tide recedes and its current slackens, sediment and floating matter borne by it are entangled among the stems in the fields of grass, and sink to the bottom. The stems, leaves and roots of the grasses, along with seaweeds, on decaying make peaty material. The mingled deposit of sediment and organic matter thus rises until it reaches high-tide level, new kinds of fresh-water plants coming in to replace the plants first mentioned, which move seaward as the water shallows, and thus marine marshes are formed, often overlaid by fresh-water plants. The process is illustrated in Fig. 143, and is often the final stage of filling of the sounds and lagoons formed by wave action, page 108.

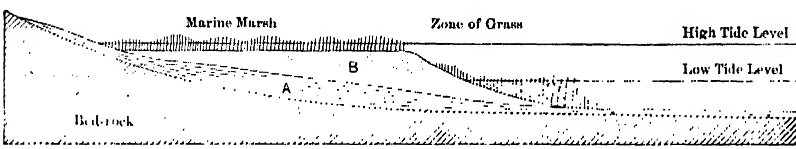


Fig. 143. — Illustrating the formation of a marine marsh. *A*, sedimentary deposits; *B*, peaty mud deposit formed by action of vegetation. Modified from G. P. Merrill.

In the low marshy regions about the deltas of great rivers, such as the Mississippi, which are sometimes inundated by the sea and sometimes covered by fresh water from the river in times of flood, similar processes prevail, although over wide stretches pure peat may be the only deposit laid down, since the vegetation may be so dense as to cause the water to quickly deposit all its sediment before reaching the interior of the swamp or marsh.

On the shores of warm seas, as on the coast of Florida, mangroves, which are small, many-rooted trees growing only in sea-water, perform a somewhat analogous function in making marshes. Their maze of roots entangle sediment and other matter, and help to form a barrier to the escape of water from the land. By this means shallow stretches of sea-bottom have been changed into swamps and marshes, as in parts of the Everglades.

Properties and Uses of Peat. — Peat varies from a brown, spongy, fibrous, or matted mass, resembling tobacco when least altered, to a fine, black, granular mud, when most changed. The latter, when dried and compressed, much resembles lignite, or brown coal. Peat, when cut and dried in the form of turfs, is much used in many countries, especially in Europe, as a cheap fuel; in North America, owing to the abundance of wood and coal, it has, up to the

present time, received little attention. The amount of it in the United States in the various bog and swamp areas is, however, enormous, being estimated by the Geological Survey at 12 billion tons of air-dried fuel; with the increasing scarcity of wood and upward tendency in the price of coal, and the discovery of the value of peat as a source of power in the gas-producer engine, it will probably have a growing use in the future.

The antiseptic quality of peat bogs has been already mentioned; this is strikingly shown in the preservation of the bodies of men and animals which became entombed in them many hundreds, or even thousands of years ago. Trunks of trees and their stumps have also been preserved, and in some places cedar logs thus buried have been extracted and used for the valuable timber they afford.

Relation of Peat to Coal. — The principles which have been laid down concerning the origin and formation of peat are of the greatest importance regarding a correct understanding of the origin of coal, and of the conditions under which it was formed. Peat is the first stage in the transformation of vegetable matter into coal. Further stages, and the kinds of coal, will be considered in a later place. It is important to observe, however, that in certain places where subsidence of the earth's crust and deposit of sediments are going on, as in the deltas of rivers such as the Mississippi and the Ganges, borings show that layers of peat, often of considerable thickness, are found alternating with beds of sands and clays, just as layers of coal are found between beds of shale and sandstone.

Reclamation of Swamp-lands. — It is estimated that over 100,000 square miles of the United States consist of swamp, bog, or inundated land, which in its present condition, although valuable in places for the timber it contains, is useless for agriculture. By the use of suitably placed canals and ditches, a very large, perhaps the greater, part of this land can be drained and rendered available for cultivation. It generally possesses a very fertile soil. Some work has been done towards reclaiming these swamp and marsh lands, as in Florida, California, and in the Dismal Swamp, with results like those shown in Fig. 144. With the closer settlement of the country and consequent greater demand for land, and with the initiation of reclamation projects in these inundated areas by the National Government, we may expect to see in the future a constantly increasing use of swamp lands.

Diatom Deposits. — It has been already mentioned (page 115) that siliceous deposits, which occur over vast stretches of the sea floor, are composed of

the shells of diatoms, extremely minute uni-celled vegetable organisms. These also live in lakes and marshes, and even in warm springs and pools, as in the Yellowstone Park, and living and dying in almost unimaginable numbers their shells form deposits, often of considerable thickness. This white, porous, chalk-like deposit of silica, SiO_2, is known as diatomaceous earth, or *tripolite*, and beds of it several hundred feet thick have been found in places. It is used for several purposes, such as polishing powder, in making dynamite, etc.

Iron-ore Deposits. — In a previous section (page 172) we have shown how, by the influence of organic matter, iron in the rocks and soils is reduced from ferric to ferrous oxide, and taken into solution. It now becomes pertinent to inquire what becomes of the iron. When

Fig. 144. — Reclaimed land from the Dismal Swamp, Va. I. C. Russell, U. S. Geol. Surv.

thus brought into solution it is leached out, and in standing bodies of shallow water, such as swamps, lagoons, or estuaries with small outlets to the sea, it may be concentrated and give rise to considerable deposits. Many of the beds of limonite iron-ore, extending from Vermont and New York southward to Alabama, are examples of these. Under some conditions these beds may be of ferrous carbonate (siderite, $FeCO_3$) directly, but usually the solution of the carbonate is reoxidized, carbon dioxide escapes, and the iron is precipitated as ferric hydroxide, limonite, as follows:

$$4\ FeCO_3 + O_2 + 3\ H_2O = 2\ Fe_2O_3 . 3\ H_2O + 4\ CO_2.$$

The most interesting feature of the process is that the oxidation from the ferrous to the ferric condition is largely performed by certain exceedingly minute vegetable organisms living in the water, which are known as the iron bacteria. These secrete the iron from solution, and change it in their cells from the ferrous to the ferric condition, thus rendering it insoluble. Although so excessively minute, yet occurring in such enormous numbers, they may give rise to large deposits.

The ferric hydroxide thus precipitated may accumulate on the bottom as *bog iron-ore*, or limonite, or, as in swamps, it may again come in contact with decaying organic matter and be changed back into ferrous carbonate. Such beds of ore may be quite pure, or, mingled with clay or sand, they may form deposits of impure limonite, clay-ironstone ($FeCO_3$), etc. This may also explain the frequent occurrence of beds of iron-ore and of coal (ancient peat bed) in the same series of stratified rocks, and why, in this case, the ore is so often ferrous carbonate. Some are inclined to believe that all beds of iron-ore found in the stratified rocks are due to these processes, and, therefore, always indicative of the former presence of vegetable life, but this is going too far, for iron-ores may be concentrated in other ways. But, in general, it may be said that such beds are presumptive of the former existence of organic life.

Constructive Work of Animal Life. — The geologically constructive work, which animal life performs, has its results chiefly in the deposits which they leave behind them. By far the greater part of these deposits is composed of carbonate of lime, a small and much less important part of phosphate of lime. The deposit of carbonate of lime through animal life takes place now, and has taken place in the past, on an enormous scale, and is a geological process of very great importance; it occurs chiefly in the sea, and is most strikingly illustrated in the work done by corals. One phase of it has already been alluded to in speaking of deposits on the sea floor, page 115.

Coral Reefs and Islands

Corals. — These are small animals of a low order of life. The individuals are called polyps, are simple in organization, consisting chiefly of a soft sac-like body containing a stomach, a mouth, and a fringe of arms, or tentacles, around it, with which they capture their food. Further details respecting them are given in Part II. One function of the animal is to extract carbonate of lime from the sea-water, and, depositing it in the lower external part of the body, to build up a stony base upon which the animal lives and flourishes. Living together in colonies, as do most of the reef-corals, this stony base grows and assumes the varied shapes seen in masses of coral, such as branching forms, plates grouped in aggregates, half spheres, etc. See Fig. 145. Coral trees or the "staghorn" corals may be 15 feet high, and the half spherical coral heads 15 feet across. Such growths support an enormous number of individual polyps. While there are many kinds of corals, the most important geologically are

the reef-building ones. These are not found everywhere in the ocean, but only where certain suitable conditions prevail. The conditions demanded are as follows: *a*, the water must not have a mean temperature lower than 68° F.; *b*, the water must be clear and salt, free from the products of land waste; *c*, the water must be shallow, not over 240 and preferably less than 150 feet in depth. An abundance of food is also necessary, and the great westward tropical ocean currents, described on page 93, seem to carry this and produce very favorable conditions for corals as they flow against the eastern

Fig. 145. — View of corals on a reef at low water. Great Barrier Reef, Australia. Saville Kent.

continental shores. Thus the eastern shores of Africa, Australia, and Central America support extensive coral formations, whereas on the western shores of these continents they are comparatively rare.

Coral Reefs. — Corals grow upward and spread laterally, and the stony base continually increases, branching out; or the coral heads enlarge. As they die, the lime carbonate base is left and, mingled with the growths of lime-secreting algæ, the shells of various kinds of shelled animals, the tubes of worms, and the bones of marine animals inhabiting the coral thickets, and with branches and pieces of coral broken from the living forms above, forms a constantly accumulating layer. The warm sea-water cements the coral fragments together, and eventually converts the deposit into a white solid limestone, upon whose upper surface the living corals grow and flourish. This forms the *coral reef*. It rises until its surface is just below the level of low tide, only occasionally laid bare at the

lowest tides for short periods, for corals can stand exposure to the air only a limited time. Over it the waves boil and break, and at its outer edges the reef-building corals thrive best, for in the rush and dash of the waves they find the most food and lime in the water, and here the latter is clearer, more aerated, and thus furnishes more of the needed oxygen.

In addition to the corals all such reefs have many other forms of animal life living on them, and some of these, such as hydroids, also contribute by lime deposits to the up-building of the reef. Even plants (nullipores, etc.) add their share by secreting lime from the sea-water, and it seems probable from recent investigations that they have been a much more important factor in helping to build the reefs by this accumulation than had been previously supposed.

Coral Islands. — The term coral island has been used in several ways, and, unless strictly defined, is liable to misinterpretation. There are a great number of islands in the tropical oceans, especially

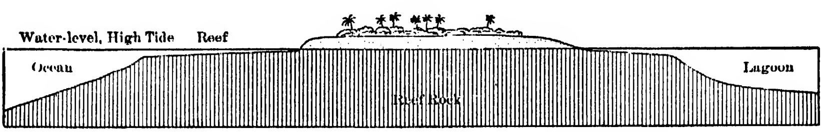


Fig. 146. — Section through coral reef and island upon it. After Dana.

in the Pacific, which for the most part are of volcanic origin, like Hawaii for example; a few are high islands composed of rocks which are not volcanic, or only partly so, like Fiji and New Caledonia. These are more or less surrounded by coral reefs, in ways which will presently be described, but they are evidently not *coral* islands. They are ordinary islands with coral reefs about them. But, by the action of the waves, masses of coral, often large coral heads, and blocks of reef-rock are broken off and thrown up on the reef, other fragments and coral sand fill in between them, and, finally, by the beating of the waves, the whole mass, resting on the broad platform of the slightly submerged reef, is compacted and rising above water becomes an island. These are true *coral islands,* consisting of the débris from organic life, the material composed of carbonate of lime secreted from sea-water.

The islands thus made are low, usually not more than 15 feet above sea-level, and from a quarter to half a mile wide, though often long in the direction of the reef. They are usually covered with vegetation, are of great beauty, and sometimes inhabited, though their lowness subjects them to the danger of being swept by the sea

in times of heaviest storms. A section of a reef with a coral island upon it is shown in Fig. 146.

Classes of Coral Reefs. — According to their position and arrangement coral reefs have been divided into three general classes, which are known as *fringing reefs, barrier reefs,* and *atolls.* The characters which distinguish them are as follows:

Fringing Reefs. — In the shallow water around any existing land where the conditions are right, corals grow, and gradually build up a platform to sea-level, forming a bench extending outward from the land edge toward the sea, as shown in Fig. 147. The width of the reef seems to depend on the steepness of the land slope; if this is great the reef is narrow, if gradual it may be several miles wide. Opposite streams coming from the land, the reef is wanting, since these produce unfavorable conditions because of the fresher and muddy water.

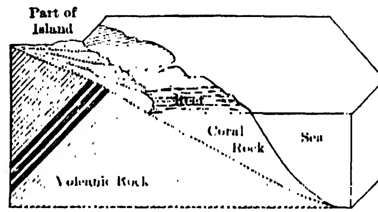


Fig. 147. — Section through land, and the attached, fringing reef.

For reasons already explained the corals chiefly grow and flourish on the outer edge of the reef. The seaward slope of the latter is very steep. As material is broken off by the waves, and rolls down this slope, it gradually becomes compacted by deposit of lime carbonate, and forms a rising talus, upon which, eventually, the corals grow and advance the reef seaward.

Barrier Reefs. — This kind of reef differs from the fringing one in that it is situated some distance from the land, with a stretch of shallow water between, forming a lagoon or channel. Many of the high volcanic islands of the Pacific are more or less completely girdled by such an encircling reef. See Fig. 148.

Openings or breaks exist in these reefs sufficiently deep to permit the access of vessels to the lagoon-channels, which thus serve as harbors; the channels, which have an average maximum depth of 200 feet, are, however, often too shallow for navigation. The barrier may be from one to thirty miles from the land; often they support islets upon them, which may be wooded. The west coast of the island of New Caledonia has a reef of this character that extends for 400 miles, while the

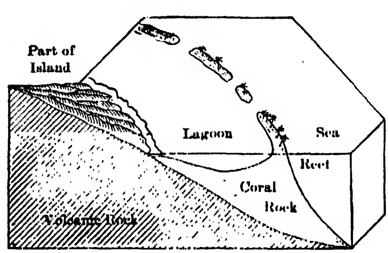


Fig. 148. — Section through land and distant barrier reef with lagoon-channel between.

greatest of all is the great barrier reef of Australia, which stretches for 1200 miles along its eastern side, with an average distance of 20-30 miles from the mainland, and with a depth of 100-300 feet in the channel. A view of a portion of this reef at very low water, with the living corals growing on it, is seen in Fig. 145.

Atolls. — These, like many barriers, are more or less imperfectly ring-shaped reefs, but without any island within, only a lagoon of comparatively shallow water, as indicated in Fig. 149. The breadth of the ring may be from 2 to 50 miles; generally there are openings, usually on the leeward side, affording access to the lagoon. The depth of water in the latter may be from a few feet up to 300, but averages about 200; on the outside the reef may descend quite sharply thousands of feet toward the ocean floor. Like the other reefs mentioned they may support wooded and inhabited islands upon them. A view of an atoll is seen in Fig. 150. Such atolls are one of the most striking features of the Pacific Ocean.

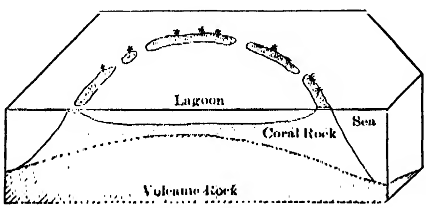


Fig. 149. — Section and plan of an atoll.

Fig. 150. — View of an atoll; after Dana, from an old picture.

Origin of Barrier Reefs and Atolls. — Fringing reefs require no special explanation; their origin is simple and may be understood from the description of them. But barriers and atolls are difficult to understand, both from their form, and from the fact that they appear to rise from the bottom of the deep ocean, thousands of feet

below the limit at which corals can grow. How then did these curious structures originate? In the attempts to answer this question processes have been invoked which make the explanations important from the bearing they have upon geological problems of great significance.

Subsidence Theory of Darwin and Dana. — An explanation which for a long time received general acceptance was one offered by Darwin and elaborated by Dana. According to this hypothesis the three kinds of reefs represented successive stages in a continuous process produced by gradual *subsidence* of the ocean bottom. The

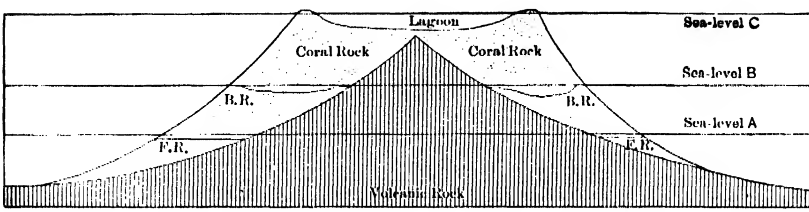


Fig. 151. — Section showing the formation of barrier reefs, *BR*, and an atoll from fringing reefs, *FR*, by gradual subsidence; sea-level remaining permanent but assuming relations *A*, *B* and *C*.

idea involved may be easily understood from inspection of the diagram, Fig. 151. Around some island, produced perhaps by volcanic agencies, corals attach themselves and grow, forming a fringing reef *FR*. The sea-level is supposed to be at *A*. As the island gradually sinks, the sea-level remaining the same, it assumes with respect to the land the position of *B*. Meanwhile the corals keep building the reef upward and, for reasons already given, most rapidly on the outer edge, and thus the fringing reef becomes the barrier *BR*. By a continuation of the process the island disappears, and the barrier becomes an atoll, as in *C*. It is understood that the rate of submergence is not greater than the upward growth of the coral reef. There are many facts which seem to confirm this theory, but as a sufficient explanation for all kinds of coral islands, objections have been urged against it.

What seems to confirm it are the facts that all gradations between the three kinds of reefs may be found, and that there are positive evidences of recent submergence in some cases, such as the dredging of dead and drowned corals from the reefs at depths below the limit of coral growth; stone houses of natives once built on the shore and now surrounded by water, etc. A boring in a typical atoll went down over 1000 feet in coral-reef rock, indicating corresponding subsidence and up-building. The topography of the coast-lines of the volcanic islands with barrier reefs also shows subsidence, since there are

no sea-cliffs cut into them, the streams have no deltas, but drowned river mouths, and the shore-lines are very irregular. These features, and others, relating to the disposition and topography of the groups of islands with coral reefs, and of atolls, have recently been strongly urged by Professor W. M. Davis as confirmatory of this theory.

The objections to this view are that it requires a general subsidence of thousands of feet of the earth's crust over such a vast region, some 20,000 000 square miles of the sea floor of the Pacific, as well as subsidence in other oceans. It has been also pointed out that in some island groups there are atolls in one place and raised coral reefs in other ones not many miles distant. Where reefs have been raised they are found not to be over 250 feet thick.

Theory of Murray and Alexander Agassiz. — This attempts to account for barriers and atolls without subsidence. We imagine first a platform to be raised in some way from the ocean floor up to the required depth for coral growth. This might happen by volcanic eruptions and up-building; sometimes the volcanic masses would protrude from the sea and form islands; sometimes they would be not very high above sea-level and would be cut away by the waves to shallow-water platforms, and sometimes, when not up to the required level, they might be raised to it by lime deposits from the shells of marine organisms. Or, as Agassiz suggests, the platform might be made by the latter method alone. Around such islands, and on the platforms thus made, coral would grow and, thriving best on the outer edges of the reef, the latter would expand and move seaward, advancing on the talus forming at its front. In the meantime the dead portion of the reef left behind, bored into by innumerable organisms, would crumble and, partly by the supposed solvent action of the sea-water and its contained carbon dioxide, and partly by the scouring of currents, would be gradually removed, and in its place would appear the channels and lagoons. Thus where there was an original island, the fringing reef would move away and become a barrier; where only a submarine platform was present, it would move to its outer edges and form an atoll.

The chief objection to this view is the great size and depth of many lagoons and channels, 30 miles wide and 200 feet deep; it seems improbable, if not impossible, that such enormous masses could be removed through solution. Moreover, the study of atolls shows that the lagoons tend to fill up rather than to deepen, that lime carbonate is depositing in them rather than being removed by solution. It also does not account for the general evidences of recent submergence mentioned.

Rise of the Water-level. — Quite recently Professor Daly has urged the importance of a rise in the water-level of the oceans as an explanation for the origin of barriers and atolls, an idea previously advanced by Thos. Belt, Upham and others. The cause of this increase of water in the oceans is at-

tributed to the gradual melting of the vast continental ice-caps which covered in a recent geological period the North and South Polar regions, and extended down into what are now temperate latitudes, as will be described more fully in a later place. They covered millions of square miles, and were several thousand feet in thickness. The gradual accumulation of this ice lowered the water-level in equatorial regions, and its gravitative effect, in drawing the oceanic water toward it, tended to lower the level still more. Daly calculates that these effects lowered the level of tropical seas from 200 to 250 feet. Owing to the colder condition of the earth, and thus of the seas, it is inferred that coral life was restricted to very narrow tropical belts. Elsewhere the islands, undefended by caps and belts of growing coral, were exposed to the erosive action of the waves, which cut wide terraces around the harder and larger ones, while small ones, and those of softer, less compact material were cut off, forming platforms at sea-level. When the ice melted, and the seas grew warmer, the corals are supposed to have returned to these islands; on the terraces around the former, growing best at the outer edge, they formed barrier-reefs, while of the submerged platforms they made atolls. Since the reefs grew upward, as the water gradually deepened from the melting of the ice, the interior lagoons and channels were formed, and these, since then, have been gradually filling up. This is taken to account for the general depth of 250 feet of the platforms below sea-level, for the usual depth of about 200 feet in the larger channels and lagoons, and for the evidences of apparent subsidence previously mentioned.

The correctness and value of this view as an explanation of the varied features of coral islands and formations mentioned, and its general bearing on geology can only be ascertained by a careful comparative study of varied groups of islands, especially of their topography, and of the relations of coral formations of past ages. It also depends on the amount of water withdrawn from the sea, and turned into ice, and the data on which this in turn depends are at present too vague to enable us to calculate it with any precision. The amount of landward cutting by wave action at the lowest stage of water-level, in view of the time demanded, would in some cases seem excessive. It is in one respect a reversal of the Darwin-Dana view, but, like that, demands a change of water-level.

General Explanation. — From what has been said in the foregoing pages it appears that widely divergent views have been, and still are, held regarding the origin of the peculiar features seen in barrier reefs and atolls. Our knowledge in several directions does not seem sufficiently extensive to afford a general explanation which would be universally accepted at the present time. It should be pointed out that the views of Darwin and Murray are not necessarily exclusive of each other. Barriers and atolls could be formed on either assumption, if other conditions were right, and outward-spreading growth and submergence might be occurring simultaneously. If subsidence were the only factor we should expect a great thickness of coral rock in atolls, whereas borings in one in the Pacific, and quite recently in Bermuda, show only a relatively thin

capping of it on the volcanic rock, which forms the main masses rising from the ocean depths. Quite recently Vaughan has called attention to the fact that there are shallow-water platforms in warm seas which, in places, are devoid of coral formations of barriers and atolls, like the one surrounding eastern Australia, which shows that the platforms antedate the settlement upon them of the corals, and are, therefore, independent of them. He also shows that the crescent or ring shape of atolls may be due to the effect of prevailing winds and currents; the apex of the crescent pointing toward the direction of current arrival. Further, recent chemical investigations show that the water in the lagoons has no solvent action but is really precipitating lime which tends to fill them up. The suggestion of a change in sea-level through melting of ice-caps may prove of value as one factor in helping us to understand the generally uniform depth of water on the shelves which support barriers and in the lagoons of atolls, and many of those features which appear obviously due to changes of water-level, without having recourse to vast subsidences of the floors of entire oceans, as needed by the Darwin-Dana theory. It should be noted, however, that other factors may produce changes of water-level. Thus, over the vast extent of the ocean bottom, which covers three-quarters of the globe, relatively slight warping movements here and there through long periods of time, causing upward and downward movements over local areas, would register themselves by changes of water-level on the shores. It seems probable that the formation of the coral-island structures is a complex one, due to a combination of several agencies, which operated with varying intensities in different places, and that we cannot advance one single factor which will cover all cases, and afford a general explanation.

Lime Carbonate Deposits; Limestone.—A great variety of animals living in the sea are constantly extracting from it carbonate of lime for their own uses. In the sea-water it exists as the soluble bicarbonate, $H_2Ca(CO_3)_2$, which the animals convert into normal carbonate, $CaCO_3$, the insoluble form, and for each molecule thus converted one of carbon dioxide, CO_2, is set free. This they do to produce hard parts which shall support or protect their soft parts. Familiar examples are the shells of molluscs, such as clams, oysters, sea-snails, conchs, etc., or the supporting structures of corals. There are also many kinds of minute free-swimming animals of low, or very simple, types of organization living in the upper layers of sea-water, which have protective calcareous shells. One important group of these is known as Foraminifera, examples of whose shells are seen

in Fig. 89. Generally they are not larger than a grain of sand. It has been found that the lime deposits in the sea are also largely due to the action of small forms of vegetable life, varieties of algæ, floating in the upper layers of the water, which secrete lime from it. See also page 112.

These varied kinds of life, small though they may be in the individual, through their enormous numbers, and working through long intervals of time, have produced by their shells and other structures deposits of carbonate of lime, which in places are of vast extent. These deposits, accumulated on the sea-floor, according to their degree of compactness and other characters, as we are able to determine them after they have been raised and turned into land surfaces, are known as *chalk* and *limestone*. Limestone, therefore, is a sedimentary deposit of carbonate of lime made by organic life in the sea.

This work is, perhaps, most conspicuously seen in the formation of the coral reefs previously described. A coral reef might be likened to a factory for the manufacture of limestone. Along with the corals a variety of other organisms are busily at work, shelled animals of different kinds, some of which bore into

Fig. 152. — Serpuline atoll. Bermuda Island. These structures formed in shallow water may be a number of feet, or yards, in diameter and are locally called "boilers."

the coral rock and help to crumble it; worms (Serpulæ), which form calcareous tubes and whose colonies may form miniature atolls, as at Bermuda, Fig. 152 and even some types of sea-weed (nullipores), which secrete carbonate of lime and produce coralline structures, while Foraminifera swarm in the water and add their quota of shells to the deposits. Nor is the deposit confined to the reefs and their immediate neighborhood. The coral rock, broken by the waves and ground up to fine sediment, is distributed over the sea-floor, the water being muddy with it after heavy storms for miles away from the reef. Such fine substance consolidated by pressure of overlying material, and by solution and re-deposition, forms compact limestone. The rock is often dense and structureless, and without fossil remains through great thicknesses, in other cases filled with corals, shells, etc. As beds of limestone are found

piled up in thicknesses of hundreds and even thousands of feet, it must be inferred that their formation has required enormous periods of time. Agassiz has estimated that it would take about 1000 years for a coral reef to grow upward 40 feet. It is especially in the warm waters of tropical and sub-tropical seas that the conditions are suitable for those forms of life which deposit carbonate of lime, and where it therefore accumulates in greatest amount. Therefore, the presence of thick beds of limestone is held to indicate warm climate in that region at the time of their formation.

Shell Limestones; Coquina. — There are many varieties of limestone, depending on the mode of formation. Thus in some there are abundant remains of some particular organism, which contributed most largely to the deposit in the form of fossils, and which gives the rock a peculiar character. It may be composed almost entirely of shells with fine carbonate of lime between them, acting as a cement. Such rocks are sometimes called "shell limestones." A light fragile rock, consisting of shells and their fragments somewhat compressed and cemented, now forming on the coasts of Florida, is known as *Coquina,* from the Spanish word for shell.

Chalk. — This well-known, soft, slightly coherent rock consists of a fine calcareous powder, which the microscope shows to be largely composed of the tiny shells of Foraminifera and microscopic plants (algæ), mingled with fragments of other shells, etc. It commonly contains hard nodules of siliceous material called flint, which are supposed to represent the concentrated hard parts of certain organisms which secrete silica.

It has been customary to consider chalk a formation produced on the bottom of the deep sea, from its resemblance to the calcareous oozes, or muds, found at the bottom of modern oceans. See page 115. It would seem, however, not to have been formed as a deep-sea deposit, since it always contains fossils indicative of shallow water, as well as skeletons of birds, pterosaurs (flying reptiles), etc. The facts in most cases would point to its having been formed in clear, shallow, and warm sea-water, free from products of land erosion.

Chemical Precipitation of Lime Carbonate. — Recent investigations by chemical and other means have shown that the ocean water, except at great depths and probably on the surface in polar regions, is saturated with carbonate of lime in solution. It is therefore obvious that if, in any way, the amount of carbonate of lime, $CaCO_3$, be increased by concentration, or the capacity of the water to contain it in solution be diminished, this substance will be precipitated. Thus in shallow areas an increase of temperature by warming the water may cause evaporation and loss of CO_2, both of which would produce precipitation, while agitation by waves would also cause a loss of CO_2 gas, and promote precipitation. These facts, which have been pointed out by Vaughan and others, show that lime carbonate must be thrown down by inorganic means, as well as by organic life, but we have no idea yet as to the quantitative importance of the process, that is, of the amounts which may thus be precipitated.

Dolomite. — Although limestones, when first formed, consist of lime car-

bonate, $CaCO_3$, in process of time they have been in places more or less completely converted into dolomite, $CaMg(CO_3)_2$. Even if not pure dolomite, if they contain any considerable quantity of magnesia, they are still often referred to as dolomite, or dolomite-limestone. While this change probably takes place in greatest amount in the sea, whose waters contain magnesium salts in solution, see page 92, and especially where the water is warm and shallow, it apparently may occur on land also, caused by several agencies, the upward movement of warm waters containing magnesium salts for example, but is more restricted in extent. Dolomite is a more stable compound than calcium carbonate and forms a denser, more insoluble rock.

Phosphate Deposits. — These, while not making geological formations of great extent and importance, are of interest and of great commercial value from their use as fertilizers for the soil. When found in sedimentary beds we ascribe their origin chiefly to the calcium phosphate of the shells of some marine invertebrate animals (brachiopods, heteropods, etc.), and the bones and excrement of vertebrate animals, concentrated often by being leached down and re-deposited. Thus they occur in Tennessee, Florida, the Carolinas, and other parts of the South. A modern illustration of their formation is seen in the deposits of guano, the excrement of sea-birds in certain places in arid regions, as on the west coast of South America. The calcium phosphate it contains comes chiefly from the bones of the fishes which form the food of the birds.

CHAPTER VIII

IGNEOUS AGENCIES; VOLCANOES

The various agencies which we have so far considered as modifying the surface of the earth, such as the atmosphere, water in its forms of rivers, seas and ice, and plant and animal life, derive the energy which enables them to move and perform their work from a source exterior to the earth: from the sun. For, without the sun, these movements would cease and the earth's surface would be dead and inert. Toward these agents the earth is passive, except as it adds the force of gravity to help them in their work. An exception to this principle may be found in the chemical work of underground water, otherwise it appears to be a general one.

We have now to consider a set of agencies which are also modifying the earth's surface, whose energy on the other hand is derived from sources within the earth itself. So far as we can judge they appear to be due, either directly to the interior heat of the earth, or to changes going on within which produce heat. We shall describe first the results as seen at the surface, and then inquire into the possible origin of them.

When we regard the changes going on within, and the concomitant heat, as geological factors, the processes and results which they give rise to at the surface may be grouped as follows:

a. Volcanoes and igneous phenomena.
b. Hot-springs and fumaroles.
c. Changes in position of the earth's crust.
d. Earthquakes as a result of *c*.

Volcanoes

General Description. — Volcanoes are elevations composed of materials collected around a vent through which they have issued from the earth's interior in a highly heated or molten condition. In its typical aspect a volcano is conceived of as a steep conical mountain with a pit-like crater at the top, from which issue from time to time gases, ashes, bombs, and flows of molten rock called *lava*. The ejection of material is termed an *eruption*, and volcanic

eruptions are to the human mind, perhaps, the most impressive of geological phenomena, from the immensity of the forces displayed, the magnitude of the results achieved, and the disastrous consequences which they frequently entail. Volcanoes are apt to vary widely from the typical form mentioned; they may be low and flattened, or high and steep; conical, or elongated and irregular in shape; while the crater may be at the top, or on the side, of variable shape, or even wanting.

In size volcanoes may vary from small cones one or two hundred feet high to those which form some of the loftiest mountains on the globe. Thus certain of the highest peaks of the Andes are formed by volcanoes, some of which are still active, as Cotopaxi in Ecuador, 19,600 feet high, with a crater half a mile in diameter and 1500 feet

Fig. 153. — Mt. Shasta, Cal. J. S. Diller, U. S. Geol. Surv.

deep, while others, like Aconcagua, 23,000 feet, and Tupungato, 21,500 feet, on the border between Chile and Argentina, and Chimborazo (20,500), in Ecuador, which apparently have no craters and are not now in activity, have geologically only recently become extinct. These are built, however, upon a dissected uplift, or platform, of much older rocks, above which they rise 10,000-12,000 feet, but in the case of the Hawaiian Islands the volcanic piles are placed on the sea-floor, some 14,000-18,000 feet below the surface, above which the highest summits project about 14,000 feet, thus making the whole mass some 30,000 feet in extreme height. In the United States the higher peaks of the Cascade Range, beginning with Mt. Shasta (14,400 feet), Fig. 153, in northern California, and including in Oregon and Washington Mt. Hood (11,300), Mt. Adams (12,470), Mt. Rainier (Tacoma) (14,500), and Mt. Baker (10,800),

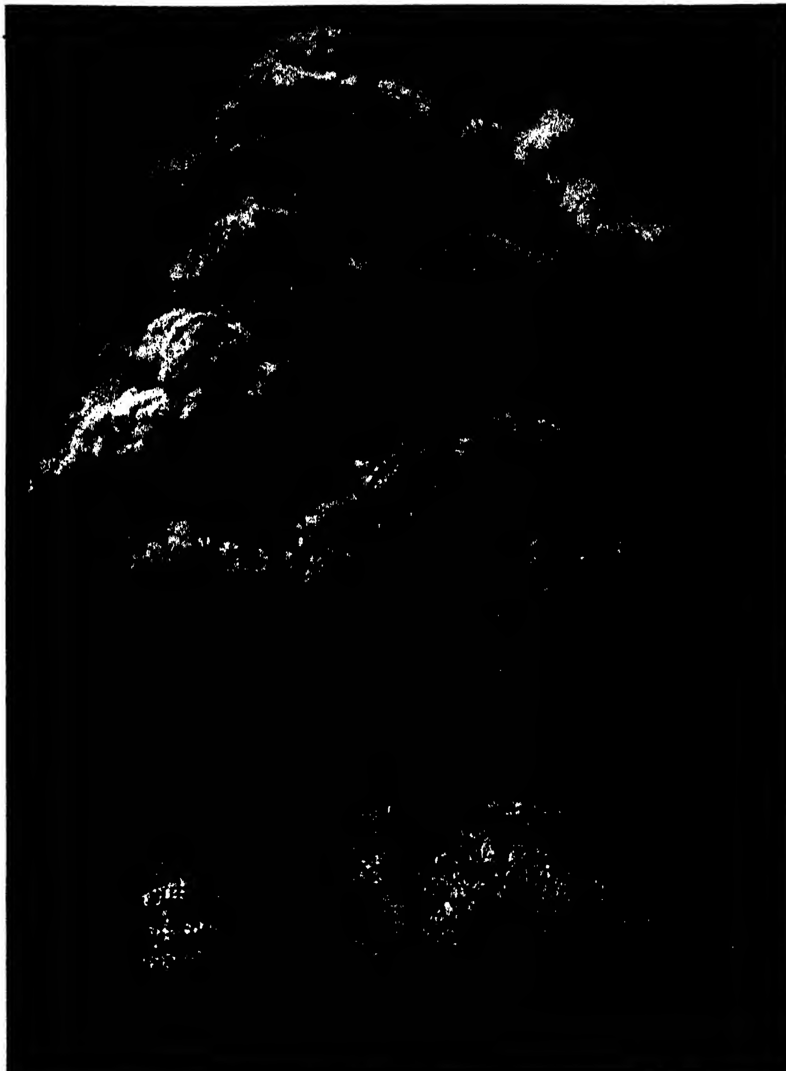


Fig. 154. — Eruption of Vesuvius, April, 1906. Seen from Boscotrecase. The volcano is about 4000, the ash cloud over 17,000 feet high.

are volcanoes, which are now quiescent, or have recently become extinct. Mt. Etna, on the coast of Sicily, rises about 11,000 feet above sea-level, and the diameter of the base of the conical pile is about 30 miles. The lower slopes are gentle and studded with many small, minor, or parasitic, cones.

Character of Eruptions. — At volcanic vents three things may be ejected, gases, liquids consisting of molten rock, and solid material in the form of fragments, and the nature of a volcanic eruption depends largely on the proportions and relations of these three things. If the eruption is violent and explosive in character then the gases have been the chief factor in its production, and solid fragmental material is the result; if, on the other hand, it is quiet in its operation, liquid rock, or lava, is the main product, and the gases play a less important rôle. We may thus roughly classify volcanic eruptions into those which are *explosive*, and those which are *quiet* in nature. When we attempt to classify actual volcanoes, according to this difference in operation, we very quickly find that, although good examples of both types may be found, a very great number, perhaps the majority, are *intermediate* in their character, that is, they sometimes erupt violently, and sometimes give rise to quiet flows of lava. In many volcanoes during a quiescent stage there appears to be a gradual accumulation of pressure, the lava rises in the conduit, and eventually the eruption begins explosively, great quantities of gases mingled with dust and stones being ejected; the pressure being to a great extent relieved, this phase is succeeded by a quieter one in which the lava escapes through rents in the cone and forms outflows on its exterior.

Explosive Type. — In the most extreme form volcanoes of this type give rise to sudden, violent, and often extremely disastrous explosions. Enormous quantities of gas are suddenly projected into the atmosphere, so thickly mingled with comminuted rock (dust and ashes), as to form vast outrushing and expanding clouds of dense appearance and dark color. See Fig. 154. The greatest known explosion of this character occurred at Krakatoa, a volcano in the Strait of Sunda near Java, in August, 1883. After premonitory outrushes of gas for some time, the great explosions occurred, which blew away over a cubic mile of material from the volcano into the air in the form of dust and ashes. This vast dark cloud is stated to have risen 17 miles into the atmosphere, completely hiding the sun by its denseness over a vast area. The noise of the terrific detonations was heard for more than 150 miles, while the disturbance in the atmosphere was registered by barometers over the whole world.

Huge waves, up to 100 feet above tide, were generated in the sea and rushed along the low-lying coasts of Java and Sumatra, sweeping far inland and destroying towns, villages, and the lives of nearly 40,000 people; they were perceptible 3000-4000 miles away.

In May, 1902, from the volcano of Mont Pelée on the island of Martinique, and almost simultaneously from that of the Soufrière on St. Vincent in the West Indies, after small premonitory symptoms, violent explosive eruptions took place. No lava was outpoured, but the intensely heated gases were so thoroughly filled with incandescent particles of rock that the heavy, fiery

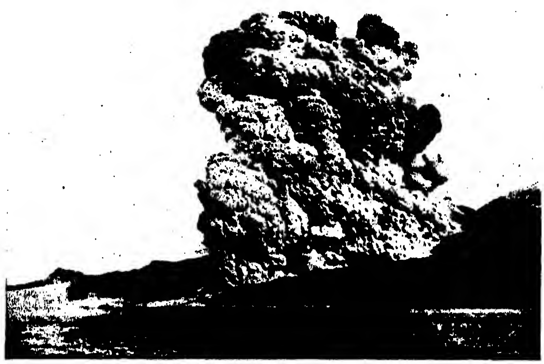


Fig. 155. — Fiery cloud of Mt. Pelée descending the mountain slope into the sea. The cloud at this moment is 7000 feet high, and moving forward at the rate of over a mile in 1.5 minutes. A. Lacroix.

clouds not only rose, but acting like liquids, rushed down the mountain slopes into the sea. Destroying all life in its course, the cloud on Martinique enveloped the town of St. Pierre and immediately destroyed it, together with its 30,000 inhabitants. On St. Vincent 2000 people perished and a broad tract of country was devastated. For many months after, Mont Pelée continued to eject at irregular intervals these incandescent clouds, one of which in Fig. 155 is seen rushing into the sea.

Intermediate Type. — Probably most volcanoes belong, or have belonged, to this class. In them an eruptive period is likely to begin with explosive activity, manifested by the projection of gases in great quantity, accompanied by solid fragmental material, bombs and ashes. In a succeeding phase liquid material issues; it may be projected by yet issuing gases, or it may break through the crater walls and produce outflows of lava, sometimes of great volume. Finally, the volcano becomes quiet, its energy for the time being exhausted; the lava may sink down in the conduit and a period of quiescence intervene before the next eruption.

While this sketches in a general way the succession of events it must not be supposed that all volcanoes of this class are alike in the character of their eruptions, or that the same one always passes through a similar set of phases at each eruption, for there is great variability in these respects. The main point is that volcanoes of this kind both exhibit explosive activity, and have also quieter outflows of liquid lava.

Vesuvius, the longest and most studied, and, therefore, the best-known volcano in the world, belongs in this class. It occupies the site of an older volcano, which in the time of the Romans appeared to be extinct, for, although they recognized its nature, they had no traditions of its having been active.

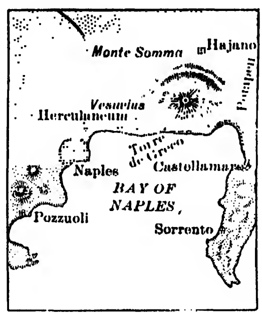


Fig. 156. — Map of Vesuvius and vicinity.

In the year A.D. 79, the volcano again became active in eruptions that destroyed the towns of Herculaneum and Pompeii on its seaward flanks. A great part of the former crater, on the side toward the sea, was blown away, or engulfed, and in its place the new center of activity, the modern Vesuvius, began to build up. This has continued until the new cone is about 4000 feet high. Partly enclosing it lies the sickle-shaped ridge of Monte Somma, the remains of the older crater, Fig. 156. The volcano is in a state of almost constant, relatively mild activity, with irregular periods of violent eruption. The last great eruption occurred in 1906, see Fig. 154. From the nature of the material composing their cones it seems probable that the great volcanoes of the northwestern United States, previously mentioned, and now quiescent or extinct, belonged in this class, as well as the active ones of Alaska and the Aleutian Archipelago.

Quiet Type. — These give rise to quiet outflows of liquid lava without explosive disengagement of gases and projection of solid material as dust, ashes and bombs. The lava in this case is very hot and possesses great liquidity. There is a more or less constant escape of gases from it, but without the catastrophic violence of the previous types. The best example is found in Hawaii.

The island of Hawaii consists of a vast mass of outpoured lavas surmounted by several cones, Mt. Kea, now extinct, 13,800 feet high, Mt. Hualalai (8,300), active in 1801, and Mauna Loa (13,700), now active and some of whose lava flows have been 50 miles long. On the eastern slope of Mauna Loa, and about 20 miles from its summit, is the great crater pit of Kilauea, of a rudely oval form, and 9 miles in circumference. Its rough stony floor of lava is a cooled and solidified crust, resting on the top of the vast column of molten rock, extending down to unknown depths in the earth's interior, Fig. 157. In some places it is not crusted over, and here lakes of liquid lava, red to white hot, and boiling from the escape of gases, may be seen. The depth of the crater

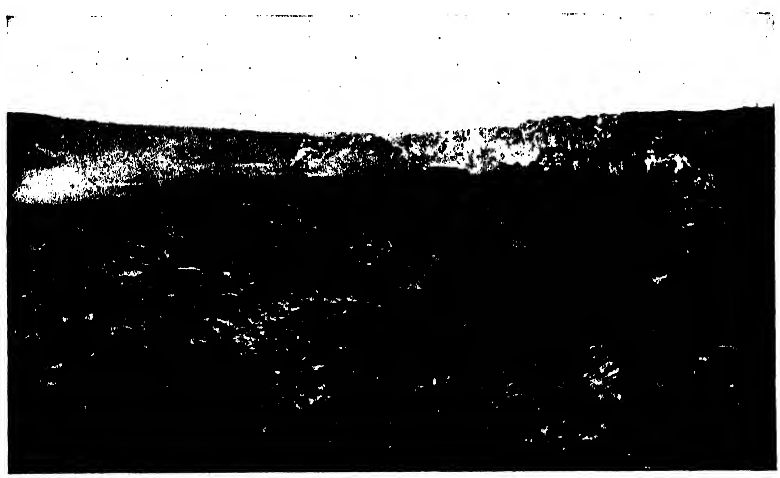


Fig. 157. — Floor of the great crater pit of Kilauea, Hawaii. To the left the view is obscured by vapors from a lava lake. J. S. Diller, U. S. Geol. Surv.

floor below the edge of the rim varies according to the height of the lava column on which it rests; after a discharge it may sink down 700 feet, then through a period of years the lava gradually rises until it stands several hundred feet higher; owing to the increased pressure, and perhaps at a time when the elastic forces of contained vapors are unusually great, the conduit walls are ruptured and outflows of lava are produced. The lava column then sinks down, carrying the crater floor with it to a lower level, until equilibrium is established. Mauna Loa acts in a somewhat similar way, but the top of its lava column is nearly 10,000 feet higher than that of Kilauea. The outflows of lava are more apt to occur through the flanks of the mountain than through the crater rim; they sometimes take place below sea-level.

Relation between Volcanoes and Magmas. — The igneous fluids of the earth's interior, which give rise to volcanic action and volcanoes, are known as molten *magmas*. When these issue out on the earth's surface, the liquid material, and the rock produced by its

cooling and solidification, are called *lava*. It must not be supposed, however, that the composition which a solidified lava might show, if determined chemically, would be also that of the magma which yielded the lava. For the deep-seated magmas contain, in addition to the mineral substances of lavas, great quantities of gases, especially water vapor, which are held in them under pressure in a kind of molten solution. As the magma rises to the surface, and the pressure is relieved, the gases escape, usually with more or less explosive energy, and give rise to volcanic activity. Since the different types of volcanoes, and of the lavas which they yield, depend in large measure on the magmas producing them, it is necessary at this point to consider the nature and composition of these molten masses.

Composition of Magmas. — As indicated above, the substances composing the earth's magmas may be divided into two classes: *a*, those which when heated are *volatile* in their nature and for the most part escape as vapors and gases, such as water vapor, carbon dioxide, hydrochloric acid, sulphurous vapors, etc., and which we shall consider in more detail later; *b*, those constituents which are *non-volatile* and remain to form the essential ingredients of the solid lavas. These latter are *silica*, SiO_2, and the oxides of six metals, *aluminum, iron, magnesium, calcium, sodium* and *potassium*. Silica in variable amount is always present in the magmas, but it has been found by chemical means that, although some metallic oxides are always present, the particular kinds may vary from almost nothing to considerable quantities. Moreover, there is a kind of general rule about this; without going into details, which will be considered later under the heading of igneous rocks, it may be said that the magmas, while forming a complete chemical series, may be divided into two classes, one in which silica and the alkali metal oxides, soda and potassa (Na_2O and K_2O), become more and more predominant, and the other in which, conversely, lime (CaO), iron oxides (FeO and Fe_2O_3) and magnesia (MgO) become higher. Lavas of the first class on cooling and solidifying may crystallize into a mass of mineral grains composed chiefly of alkalic-feldspar,* often with quartz, and are called *felsites;* in the second class alkalic-feldspar is subordinate, and quantities of lime, iron and magnesia minerals, such as iron-ore, pyroxene, lime-feldspar, etc., are formed; lavas of this kind are termed *basalt*. Felsites are generally light colored, while basalt is very dark to black, and heavy from the iron minerals.

These characters and relations may be summarized in the following table:

* For description of these and other minerals see Appendix A.

Magmas consist of	*a.* Volatile substances; Gases and vapors, e.g. water, CO_2, etc.
	b. Non-volatile substances; Constituents forming solid material, lavas.

	Chief constituents	*Chief minerals*	*Resultant rock*
Lava	*a.* Much silica; alumina, alkalies.	Alkalic-feldspar, quartz, etc.	*Felsite* (*light*).
	b. Less silica; lime, iron, magnesia.	Pyroxene, lime-feldspar, etc.	*Basalt* (*dark*).

Relation to Volcanic Eruptions. — The felsite lavas, or rather the magmas which produce them, are, even at very high temperatures, up to over 2000° C., thick viscous liquids, apparently from the high percentage of silica they contain, the amount being in some kinds as much as 75 per cent of the whole. For this reason the contained gases, when the magma rises into the upper part of the conduit and the pressure is relieved, escape from it with difficulty, and often with violence, giving rise to explosive eruptions. Hence the lavas which are found in volcanoes of the explosive type are apt to be of the felsite kind, as in Mont Pelée, or of kinds intermediate between it and basalt, such as that called andesite, which occurs at Krakatoa, Cotopaxi, etc. On the other hand the basaltic magmas, with about 50 per cent of silica, are very much more fusible, and remain quite liquid down to much lower temperatures, probably 1300° C.; the gases escape from them readily, but without explosive violence, as illustrated in the lava lakes of Kilauea in Hawaii. Thus quietly eruptive volcanoes yield basalt as a lava.

The above statement indicates the general rule; it does not mean that basaltic volcanoes never have explosive eruptions, for a basaltic magma may become cooled in the conduit, and in consequence be viscous, and thus permit the escape of magmatic gases only with difficulty and explosive energy. Many examples of this might be mentioned. The explanation applies chiefly to the two extremes and indicates what is probably the most effective cause for the explosive and quiet types of volcanoes. The intermediate type of volcano may be due in part to the intermediate kind of magma, or to this combined with variations of viscosity at different periods, as well as variations in the supply of gases.

Products of Volcanoes

Gases. — It has been already shown that the products yielded by volcanoes may be divided into three general classes, gases and vapors, solid fragmental material, and liquid rock or lava. These may be now considered in more detail, beginning with the gaseous substances. The quantity of vapor discharged by active volcanoes is immense, and is indicated by the height and volume of the cloud with which many eruptions begin. This consists of the dust and

ashes borne aloft by the uprushing column of gases. The great quantity of vapor, thus discharged into the atmosphere, by condensation may give rise to heavy downpours of rain in the vicinity of the volcano, and, owing perhaps to the friction of the particles and to atmospheric disturbance, the eruptions and rains are accompanied by striking electrical displays and lightning. Although it is not directly known what the composition of the gases is in volcanic eruptions, and it probably varies in different cases, from a quantity of indirect evidence it is assumed with good reason that it is chiefly water vapor, or steam. As an instance of the quantity of water which some believe is discharged, Fouqué estimated, that from one of the subsidiary cones of Mount Etna, there was discharged in 100 days in the form of steam, the equivalent of over 460,000,000 gallons of water.

Quite recently some geologists, basing their opinions largely on the experiments and ideas of Brun, have suggested the view that water vapor is of minor importance, or wanting, in volcanic phenomena. But the investigations of Day at Kilauea refute this, and show that water escapes from even this quiet basaltic magma in considerable quantities, and that, by means of iron pipes suitably placed, it could be collected directly from it.

In addition to the water, the different kinds of gases and volatile products exhaled by volcanoes would make a long list. Not only are these given off from the vent itself, but the outflows of lavas, for weeks and even months, after their extrusion continue to emit them as they cool and harden. It appears that in the vents and from the hottest lavas, hydrochloric acid, hydrofluoric acid, and even hydrogen are given off, and to the mixture of the latter with oxygen and its sudden combustion are sometimes ascribed the explosions in the conduit. Various compounds of sulphur are emitted by some, but not all, volcanoes, such as sulphuretted hydrogen, H_2S, and sulphur dioxide, SO_2. In declining stages of activity, and in less heated areas, carbon dioxide appears to be one of the chief products. Nitrogen and boric acid, H_3BO_3, may also be mentioned. Although little is known concerning the chemical conditions of these substances in the magmas, the knowledge of their presence, and what we have so far been able to learn about them, are of great value and interest in their bearing on important problems in geology, such as the origin of hot-springs and geysers, contact metamorphism, and ore deposits, as we shall see later.

Fragmental Products.—These are the materials blown into the air by the sudden liberation of the gases. They may be derived from the crust, ~~or plug~~, of hardened lava left in the upper part of the conduit after a previous eruption, from rock material torn from its walls or from lava projected from the upper part of the liquid column by the violent expansion and expulsion of gases from the magma due to relief of pressure as it rises to the surface. In the latter case, although the material may start on its aerial flight in a liquid

condition, it generally hardens in its passage and falls in solid form. The pieces of rock, and the particles of magma driven upward and solidified, are of all dimensions, from dust so fine that it may float in the atmosphere for several years, to large masses of several hundred pounds in weight. According to size, they are roughly classified as follows: pieces the size of an apple, or larger, are called *bombs;* those the size of a nut are termed *lapilli* (meaning little stones); those the size of a pea are volcanic *ashes,* while the finest is *volcanic*

Fig. 158. — Volcanic bomb, Lipari Islands.

dust. The ashes and lapilli are frequently spoken of as *volcanic cinders,* and cones made of them as cinder cones. It should be clearly remembered, however, that while these terms are used to describe the appearance of the products, the latter are not the result of ordinary combustion. An example of a volcanic bomb is seen in Fig. 158.

The objects described above are, in part, composed of compact solid rock and, in part, are apt to have a spongy, cellular, or vesicular character. This latter is due to the fact that, while the major part of the gases are passing into the air, and carrying the fragments with them, a minor part are expanding in the particles of liquid, puffing them up into the cellular forms. Although the bombs, lapilli, and most of the ashes fall in the immediate vicinity of the vent, and thus help to build up the cone, the dust may be carried long distances, hundreds of miles or more, by the prevailing winds, and be thus spread over an immense area. Huge quantities are discharged in great eruptions, amounting to many millions of tons. See Fig. 154. Such dust showers may be very destructive to vegetation, and even to animal life, but the soil ultimately yielded by them is very fertile.

Liquid Material; Lavas. — In volcanoes whose periods of eruption begin explosively, the liquid lava generally issues later, after the

vent has been cleared. The cone is not a structure of great strength, and is liable to be ruptured, or fissured, by the explosions and the pressure of the lava column, and hence the outflows are not apt to take place over the lip of the crater, but to issue through fissures in the side of the cone. It may even happen, especially when the cone is composed of cinders, that, unable to withstand the pressure, one side may give way, allowing a flood of lava to rush out from the breach thus made.

The appearance and character of a lava stream, and the material produced by its solidifying, depend on several things; on the chemical nature of the magma, on the degree of viscosity of the molten fluid, and the extent to which it yet retains dissolved gases. On the chemical composition will depend the nature of the rock, whether it will be a light-colored felsite, or a black basalt, or something intermediate, as previously explained. On the viscosity will depend the rate at which the lava will flow, the distance to which the stream will extend, and in large measure the appearance its surface may present. When it issues, the lava is red, or even white hot. It soon cools on the surface, darkens, and crusts over. If very viscous the under part may yet be in motion, the crust breaks up into a mass of rough, angular, jagged blocks of rock, which are borne as a tumbling, jostling mass on the surface of the slowly-moving flow. When, eventually, the latter comes to rest and hardens, the lava field produced is extremely rough and difficult to traverse. See Fig. 159. Such lava fields in Hawaii are called *aa* by the natives.

On the other hand very liquid lavas, like those of Kilauea and Mauna Loa, may harden with much smoother surfaces, which exhibit, however, curious ropy, curved, wrinkled, or twisted and billowy forms, as seen in Fig. 160. Lava surfaces of this kind the Hawaiians term *pahoehoe.*

Very liquid lavas may move with considerable rapidity, up to, perhaps, ten miles an hour, depending on the slope, Fig. 160; as they cool and become viscous the motion may be almost indefinitely slow, the stream creeping onward, possibly, for several years.

Sometimes on slopes, after the lava has crusted over, the liquid portion beneath may run out from below, leaving beneath the hardened surface long galleries, tunnels, or caves. On some cones the natural downward drainage may pass into these, disappear from view, and issue again below in the form of springs. This may be, in part, the cause of the springs around Mt. Shasta.

In some cases the magma, or lava, ejected is too viscous to flow; it may then pile up in a great dome on the surface. This is chiefly,

Fig. 159. — Rough surface of an advancing lava flow; *aa*, lava. Vesuvius.

Fig. 160. — Flow of basaltic lava running down a stream bed, the water of which is turned into steam. This lava, if cooling as seen, would have the pahoehoe surface. Hawaii. J. S. Diller, U. S. Geol. Surv.

if not wholly, confined to the felsite varieties of lava. Domes of lava have been observed in central France, Bohemia, Germany, etc., and are thought to have been formed in this way. They probably exist elsewhere. After the violent eruptions of Peléc, in 1902, had cleared this orifice, the column of felsite lava that filled it and hardened into rock was pushed up so that it rose like a vast tower into the air above the volcano, until it attained a maximum height of 1000 feet. See Fig. 161. Gradually it crumbled from explosions of gases into a mass of blocks.

Fig. 161. — Rock tower of Mont Pelée, Martinique. 1000 feet high. A. Lacroix.

Effect of Contained Gases; Vesicular Lava. — That the lavas, even after their issuance, still contain dissolved gases is abundantly shown, not only by the clouds of steam which may issue for weeks and months from them, but also by the structures which they assume as they cool into stone. Thus the upper part of the flow, especially in viscous lavas of the felsite class, may be so puffed up by the innumerable bubbles of vapor in it, expanding on relief of pressure, that it may assume the character of a glassy froth. Such rock froth, which is usually white or light colored, is known as *pumice,* or *pumice-stone.*

In more liquid lavas, especially those of the basalt class, the bubbles are larger, and the rock has a spongy, cellular, or vesicular character. These porous, cindery, or slag-like forms are called *vol-*

canic scoria. They are usually dark to black, or reddish. See Fig. 162.

Pumice, scoria, and vesicular forms are characteristic features of the upper surface of lava flows, and they constitute also a major part of the coarser fragmental material, such as bombs and lapilli, which helps to make the cone. See page 204.

Fig. 162. — Volcanic scoria.

Crystallization of Lavas; Glass and Stone. — After lavas have been poured out and have solidified they usually present the ordinary appearance of *stone,* but sometimes, instead, that of *glass.* The reason for this seems to be as follows. If the liquid is not too viscous the chemical molecules composing it will have capability of motion, and will arrange themselves into definite compounds, that is, will crystallize into mineral grains, or crystals. It may be that the crystal grains are large enough to be readily seen and the kind of mineral determined, or they may be so minute that the lava has a homogeneous appearance; nevertheless if crystallization has taken place the lava has the aspect of stone.

On the other hand, if the lava is extremely viscous, or quickly becomes so through rapid cooling, the molecules may not be able to arrange themselves, or crystallize, into minerals, and the mass solidifies as a homogeneous substance, that is, as a glass.

Thus while lavas ordinarily, in hardening into rock, adopt a stony aspect, under certain conditions they may assume glassy forms. This occurs chiefly with felsite lava, for, as previously explained, this kind is usually the more viscous. Volcanic glass is called *obsid-*

ian; less commonly, in allusion to its luster and appearance, pitchstone.)

In some cases the obsidian is pure glass, in other ones a mixture of glass and crystals. In the Yellowstone Park, Obsidian Cliff presents a section of volcanic glass 100 feet thick, which has cracked into columns in cooling. Such a thickness of purely glassy lava is unusual. It is chiefly on the edges and upper surface of lava streams that these glassy forms are found. Primitive peoples, before they gained a knowledge of metals, made much use of obsidian for making knives, arrow and spear points, etc., in a manner similar to their use of flint.

Varieties of Volcanic Cones and Craters

Kinds of Cones. — The nature of a volcanic cone depends on the kind of material of which it is built. If composed wholly of fragmental products it will be very high and steep in proportion to its

Fig. 163. — Cinder cone, showing steep angle of repose of lapilli. Outline as given by a photograph of Mayon volcano in the Philippines.

size because the fragments fall around the vent as solid pieces, and the angle of slope is that of the angle of repose for such broken rock pieces. Moreover, as lapilli and volcanic ash are very angular, rough and clinging, slopes of 40 degrees may be attained without sliding of the accumulating mass. Cones of this kind are often called *cinder cones,* and they are characteristic of volcanoes of the

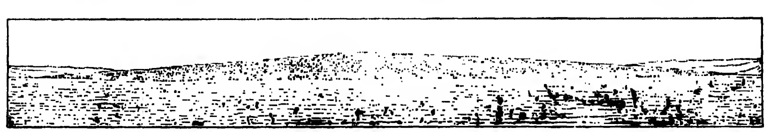


Fig. 164. — A lava cone, to show contrast with Fig. 163. From the Snake River plain, Idaho.

explosive class, Fig. 163. In contrast with them *lava cones,* formed entirely by quietly outflowing liquid lavas, like that of Mauna Loa, and shown in Fig. 160, are necessarily very low and flat in proportion to their size, the angle of inclination being less than 10 degrees. See Fig. 164. These belong to the quiet types of volcanoes. Most

volcanoes, however, and this includes the greater part of the largest ones in the world, are of the intermediate type in their eruptions, and, in consequence, their cones exhibit a form intermediate between those just described. For they are built up, sometimes by the fall of ashes and lapilli when they are explosively active, and sometimes by lava flows when the eruption is quieter. This is the character of the great cones of the Pacific States, Mts. Shasta, Hood, Rainier, etc.

In the larger volcanoes those eruptions which often break out on their lower flanks give rise to smaller, subordinate, or "parasitic" cones. Mt. Etna is surrounded by over 200 of these, some of which are nearly 700 feet high. San Francisco Mountain in Arizona, an extinct and partly eroded volcano, exhibits a number of such minor cones, some of them remarkably well preserved. As an active volcano grows, the earlier parasitic cones may be buried and concealed under later accumulations, or, in declining stages of activity, the eruptive energy may show its last efforts in the formation of them, as appears to have been the case at the San Francisco volcano, just mentioned.

Calderas; Explosion and Subsidence Basins. — The term caldera, from the Spanish for caldron, is applied to crater-like basins of great size, especially those which are very broad as compared to their depth. The name is taken from the huge pit in the Canary Islands, called La Caldera, which is from three to four miles wide and faced inwardly by lofty cliffs 1500 to 2500 feet high, except on one side where the wall breaks down to the sea. From without, at a distance, the general aspect is that of a huge cone broadly truncated. Many examples of such great calderas are known in various parts of the world, and a study of them has led to the view that, in some cases, they have been caused by gigantic explosions which have blown away a great part of the original cones as dust and ashes, leaving the calderas to mark their sites, or, perhaps more generally, that they have been produced by the subsidence of the column of liquid lava, leaving a great cavity, which the central part of the cone subsided into, and more or less filled up, the remnant of the cone outside making the caldera, or by a combination of these two causes.

Thus Krakatoa in its explosive eruption of 1883, previously alluded to, appears to have blown away a good part of the original volcano, and to thus suggest how part of the calderas are formed, although it is possible that another part may have been engulfed by the subsidence of the lava. The remnant left may mark the site of a partial caldera. The best instance of a caldera in the United States is found in Crater Lake in southern Oregon. This lake occupies a caldera at the summit of a broad sloping volcanic mountain in the Cascade Range, and is about six miles long by four broad, 2000 feet deep, and encircled by steep cliffs 500 to 2000 feet high, Fig. 165. An island

in it made by a small but perfect cone of volcanic material indicates a feeble renewal of activity after the principal subsidence. The caldera, if emptied of its water, would appear as a great basin. The reason for believing that the caldera was formed by subsidence of the lava column, and engulfment of the greater part of a former cone, rather than by explosion, lies in the existence of glaciated valleys leading up the outer slope of the mountain, until they abruptly end as notches in the cliff wall, and in the absence of the débris which an explosion would have spread over the adjacent outer slopes. The former mountain, to which the name of Mt. Mazama has been given, is conceived to have had about the size and general character of Mt. Shasta, and during the glacial period to have been heavily capped with snow and glaciers.

It may be noted here that many craters and calderas of extinct, or resting, volcanoes are filled with water, giving rise to lakes. Several of the circular lakes of Italy, surrounded by volcanic ejections, like Bolsena and Bracciano, are regarded by some geologists as marking the site of great calderas.

Fig. 165. — Part of the basin and wall of Crater Lake, Oregon. Note the small cone within. J. S. Diller, U. S. Geol. Surv.

Explosion Pits. — It has happened in some cases, where volcanic activity has begun, that it has proceeded no further than the initial explosions which have forced a vent through the country rock. The material blown out may make a low slight ridge around the pit, but no real extensive cone is built up. Sometimes volcanic products, such as pumice, cinders, etc., are mixed with the fragments of the country rocks. Such basins may be from a few hundred feet to several miles in width, and in humid regions they are usually filled with water and form lakes. Some of the best examples of them are found in the region west of the Rhine in Germany, known as the volcanic Eifel. They are there called *maars* (German, *maaren*), like the Pulvermaar, etc. A pit which strongly resembles a maar exists at Coon Butte in Arizona. The basin sunk in the plain is about 3/4 of a mile in diameter and 500 feet deep. The presence of meteoric iron in and about it, and other features, have led to the view that it was caused by the impact of a huge meteorite, and is probably not of true volcanic origin.

Rebuilt Volcanoes. — Not infrequently it happens that after a caldera has been formed, either by subsidence, or by explosion, or

both, a renewal of volcanic activity starts building up a new cone within it. This is shown on a small scale at Crater Lake just mentioned, but one of the best examples of it is seen in Vesuvius, which has built itself up in the old crater ring of Monte Somma, as explained on page 199. From this rebuilding within the older crater wall there results a cone-in-crater structure, of which there are many examples. The vast crater-like pits, which are so common on the surface of the moon, frequently show this arrangement, suggesting an analogous origin for them. It is conceivable that Vesuvius, before it becomes extinct, may go on increasing in size until the old caldera is obliterated; in this case it would be a completely *rebuilt volcano.*

Structure and Dissection of Volcanic Cones

Structure of a Composite Cone. — If a column of molten magma be forced upward through the superficial crust of the earth until it reaches the surface, the relief of pressure will enable it to commence

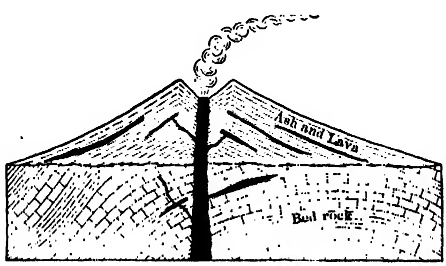


Fig. 166. — **Ideal section through a volcano. The dark layers in the cone are buried flows, or injected masses.**

discharging its dissolved gases and vapors. It may be that the pressure of the contained gases is too great for the last upper layers of bed-rock to restrain until the magma reaches the surface; these rocks may be blown into the air, and a vent drilled ahead of the rising column of lava. Arrived at the surface, an outflow may take place quietly, or, if the magma is too viscous for this, explosions may continue and material be blown upward. By the falling of the fragments the cone is built up, somewhat as seen in the diagram, Fig. 166. The pieces cannot, of course, fall back against the uprushing column of gases and cover the vent; they must fall outside of the latter, the heaviest and largest first and nearest to it, the smaller and lighter later and farther away, the distribution of the lighter depending much on the wind. Thus the cone builds as a circular ridge upon whose crest is the heaviest deposit of material,

which tends to roll and slide both ways, outwardly away from the center and inwardly down the crater toward the vent. This forms the cone and crater, and certain features regarding their structure follow as a sequence of this mode of formation.

Tuff and Breccia. — The deposits of successive eruptions will be marked by layers, some of coarser, some of finer material, in each of which, if not composed of uniform-sized particles, there is a gradation from coarser at the bottom to finer at the top. Thus there

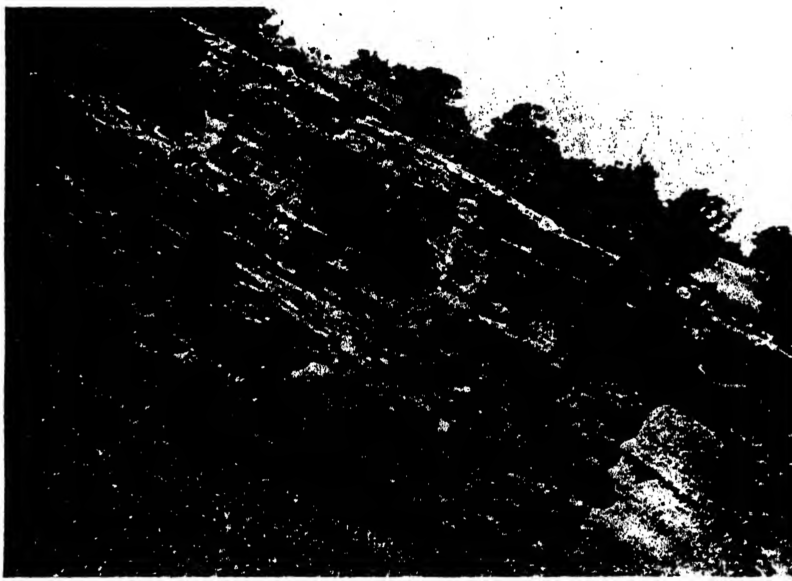


Fig. 167. — Inclined beds of volcanic ash. Part of a former cone at Trinchera, Colo. W. T. Lee, U. S. Geol. Surv.

arises a rude stratification, or bedding, the beds sloping down and out from the crater edge, Fig. 167. The bombs, lapilli, and ash composing them gradually become compacted by their weight, and by the infiltration and deposit of cementing substances, into a more or less friable, porous rock called, when composed of the coarser materials, *volcanic breccia,* and when of the finer dust and ashes, *volcanic tuff.* In the crater the fragments are larger, often large blocks of rock, and they usually form a tumultuous, mingled mass without order or arrangement, filled in with finer material, the whole called volcanic *agglomerate.*

Lava Flows and Dikes. — In addition to the beds of tuff and breccia, there are in most volcanoes flows of liquid lava down the

outer slopes of the cone, as previously described, and as these harden into solid rock they help to protect the softer layers of tuff and breccia from erosion, and to give strength to the mass. Since the lava rarely overflows the crater, but, especially in high cones, breaks through fissures, or vents, lower down, these latter also become filled with lava which hardens into rock. These rock-filled fissures are called *dikes*, and like ribs they also serve to strengthen the structure. Thus a vertical section through a volcano, as shown in Fig. 166, shows a central core of magma surrounded by beds of tuff and breccia mingled with flows of lava, which are cut in a general radial direction by dikes. This discussion gives us an idea of the general structure of a typical cone, one formed by the intermediate type of volcano; there are, of course, many variations from this, as may be inferred from what has been previously stated.

Fig. 168. — Vesuvius in 1906, showing trenching by ravines in the ashes after the great eruption. Photo by F. A. Perret. Courtesy of Harper's Weekly.

Dissection of Volcanoes. — At every stage of its existence a volcano is subject to the agencies of erosion and weathering, which tend to cut down all prominences on the earth's surface. Its height and appearance at any given time are the result of the balance between these forces and the upbuilding one of vulcanism. Even active and growing volcanoes are commonly trenched and scored by ravines and gulches. After eruptions, when the cones are covered with fresh deposits of dust and ashes, the latter become so saturated with water from the rainfall that they may give way in places and slide down as flows of liquid mud, leaving ravines, which are enlarged by subsequent storms. See Fig. 168.

As soon as a volcano becomes extinct the ravages of erosion are unchecked, and the period of dissection ensues. The lighter tuffs and breccias are carried away more easily and rapidly, the harder,

more compact and resistant flows and dikes of lava, and the parts protected by them, more difficultly and slowly. It is, however, often surprising for how long a time cones, composed of mere cinders loosely piled, will resist erosion and retain their form; the reason for this appears to consist, partly in the clinging character of the rough fragments, and partly in their porosity, which allows the rainfall to sink through without causing downwash.

As erosion progresses, the mass of rock formed by the solidification of the magma in the central conduit is likely to be brought to view, provided the magma column was not withdrawn before the volcano became extinct. In the latter case, the site of the vent will probably be marked by a mass of agglomerate. With continuing erosion and

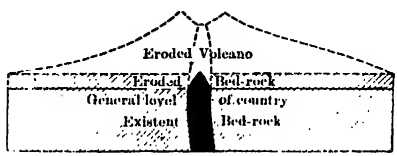


Fig. 169. — A volcanic neck. Black shows mass of volcanic rock through erosion projecting above general level of country.

the disappearing of the cone, the central rock mass, owing to its greater resistance, is liable to form a decided prominence, and, even when erosion has finally swept away all external evidences of the cone and bitten deeply into the underlying rocks, it may remain projecting, a monument to the vanished volcano. A rock mass of this kind filling a former conduit is termed a *volcanic neck*. See Figs. 169 and 251. Here we must pause, for this carries the dissection of the volcano to its very root.

Extinct volcanoes are found in every quarter of the globe and in great numbers of regions where volcanic activity has long since disappeared. Every stage of dissection is represented among them from cones only slightly worn to those so thoroughly eroded that the original shape has been entirely lost, but whose central rock core, outlying concentric masses of lavas, tuffs and breccias, and radial dikes still plainly show their former existence. The general region of the Rocky Mountains, once a theatre of active vulcanism, is now strewn in many places with the wrecks of former volcanoes. A good example of this is found in the Yellowstone Park and surrounding country, where, as we shall see later, the spark of vulcanism still lingers. So deeply eroded are the volcanoes that their remnants now form a region of most varied and irregular topography.

Volcanoes and Deep Masses of Magma. — In the preceding paragraph there has been sketched the structure of the volcano down to a conduit filled with magma coming from below. We should not,

however, leave the subject of volcanic activity, and the structures it gives rise to, at this point, before stating that volcanoes are only one phase, the surface manifestation, of the general movement of masses of magma from unknown depths below into the upper region of the earth's outer shell. Although these masses of magma may attain the surface, and volcanoes or lava flows result, often they may not, but remain below intruded among the rock layers of the shell, and there cooling and solidifying, give rise to rock-bodies of varied shapes and of sizes from a few feet in thickness up to miles in extent. Since a proper understanding of them demands a knowledge of the structure of the outer shell, they are best treated under the heading of Structural Geology, where they will be found described and classified.

Such deep bodies of magma form, then, what is known as intrusive masses of igneous rock, and every extinct volcanic conduit, if it could be traced downward, would be found to prolong itself into some such intrusive rock mass below, or, if active, into a body of magma which in time will become one.

Life and Distribution of Volcanoes

Age of Volcanoes. — We have very little knowledge of the length of time represented by the life of active volcanoes. Undoubtedly it must vary greatly in different individuals. We know, for example, that Etna has had the same general character for the last 2500 years. We can only be sure that the piling up of such vast masses of material as are represented in some of the great volcanoes must have required, from the human standpoint, a vast lapse of time. On the other hand, we know, by a variety of considerations, that the present active volcanoes are, from the geological standpoint, recent affairs, a fact which indicates to us in one way the great length of time involved in the past history of our earth.

It is also difficult to say when a volcano is extinct, because long periods, hundreds of years, may elapse between eruptions. In the Middle Ages, Vesuvius had been so long dormant that its crater was filled with vegetation and gave no sign of life. But in 1631 it became violently eruptive, and has since been intermittently active.

New Volcanoes. — Within the period of recorded human knowledge a number of volcanoes have begun their existence, and many of them are still active. Vesuvius is, of course, the most noted case of this, but other examples are seen in Jorullo in Mexico, which came into being Sept. 28, 1759, in the midst of a cultivated plain,

and is now about 4,300 feet high, and in Izalco in Salvador, which began in 1770, has been almost continuously active since then, and is now over 6,000 feet high.

No well authenticated instance of a volcanic eruption is known to have been witnessed within the limits of the United States proper until May 1914, when explosive eruptions, which have since continued at intervals, began at Lassen's Peak in northern California. The eruptions have been chiefly of gases, ashes, and stones. What appears to be the latest volcano in the United States is found in a cinder cone in the neighborhood of Lassen's Peak. See Fig. 170. It is 640 feet high above its base with a crater about 750 feet in diameter

Fig. 170. — Cinder Cone, near Lassen's Peak, Cal. J. S. Diller, U. S. Geol. Surv.

across the top and 240 feet deep. After the cone was formed a large flow of basaltic lava burst from it, and nearly filled a lake upon whose border it was situated. It then, apparently, became extinct. From the trunks of trees still standing, which were killed by hot ashes at the time of its early eruptions, and from the age of those now growing on these ashes, it is inferred that the volcano began somewhat over 200 years ago. The outflow of basalt was considerably later.

Distribution of Volcanoes. — A study of the distribution of volcanoes over the world shows that, if we consider the present active vents, perhaps 500 in number, and those cones which have suffered so little erosion that they may be considered dormant, or only recently extinct, of which there are several thousand, they have a general tendency to be grouped in long lines upon the earth's surface. The most marked one of these is the great zone which borders the Pacific Ocean; it passes northward along the Andes, through Central America into Mexico, through the United States and Canada to Alaska, then along the Aleutian chain to Asia, and turning south-

ward through Kamchatka, Japan, and the Philippines it crosses the East Indies, and by various island chains again passes into the Pacific. Certain portions of this belt, like the Andes and the Aleutian chain, are remarkably linear and well developed. Another great general zone has an east and west direction, from Central America through the West Indies; it is then continued through the Atlantic

Fig. 171. — Map showing distribution of active or recently extinct volcanoes in the Eastern Hemisphere. On S. L. Penfield's stereographic projection.

by the Azores, Cape Verde and Canary islands, runs through the Mediterranean, through Asia Minor and Arabia, and is continued by the long chain of the East Indies, where it crosses the previous one, out into the Pacific. This linear disposition occurs not only on a large scale, affecting series of volcanic groups, but on a small one as well, influencing the distribution of the volcanoes composing the individual groups. It may be studied by referring to Figs. 171 and 172.

Volcanoes are found both on the continents and in the oceans,

the true oceanic islands seeming to be entirely volcanic. Notably in the Pacific there are great numbers of them, many extinct or dormant, some still active, and here again in many cases they are grouped in lines, and stand on the submarine ridges which rise from

Fig. 172. — Map showing distribution of active or recently extinct volcanoes in the Western Hemisphere. On S. L Penfield's stereographic projection.

the ocean floor. From the fact of linear arrangement has been drawn the important deduction that volcanoes are, in general, situated on, or near, lines of fracture, folding, and weakness in the earth's crust.

The idea of the connection between volcanoes and fracture lines in the earth's crust has in many cases been pushed too far. Undoubtedly lines of fracture and weakness have proved favorable sites for volcanic action, not only for a time, but in places for long-continuing geologic periods, and this has greatly influenced their origin, situation and arrangement. But, on the other hand, it seems clear that a volcano, or a group of them, may originate where no definite connection between them and any fracture line can be shown to exist. And in places no tendency to a linear arrangement in the

group may be seen. It appears that the volcanic forces were sufficiently powerful to find an outlet without needing the aid of a fracture. A good example of this may be seen in the Highwood Mountains, a group of extinct and greatly eroded volcanoes situated on the great plain of central Montana. While the remaining tuffs, breccias, lava flows, and dikes, composing this group, and their arrangement and attitudes, show clearly the cones that once existed, erosion has dissected them so deeply that the shapes of the cones have been lost, the central conduits now filled with the massive rock are exposed, and their relations to the sedimentary bedded rocks through which they were forced laid bare. There is no evidence of any profound breakage or displacement of the crust on which they could be placed, nor do the conduits show linear arrangement.

A striking instance of how little influence favorable disposition of surface topography may have in determining the site of volcanic action, which in the immensity of its power appears to disregard such minor considerations entirely, may be seen at the Grand Canyon of the Colorado. Uninfluenced by its 5000 feet or more of depth, volcanoes have broken out upon its very rim, instead of in its depths, and their lavas have flowed down into it, thus showing also their recent origin compared with that of the canyon.

The fact that almost all active volcanoes are either situated in the sea, or in a general way around its borders, and when inland are in, or near, lakes has led many to believe there must be a necessary connection between the surface waters and the cause of volcanic activity. This question will be considered later in the discussion of the origin of volcanoes.

Submarine Eruptions. — From the great number of volcanic islands in the sea, the real oceanic islands being of this nature, it is evident that in times past tremendous eruptions and vast outpourings of lava have occurred on the sea floor. The volcanic chain of the Hawaiian Islands is an example of this. Instances of actual eruptions beneath the sea have been observed in a number of cases and recognized by the issuance of vapors, ashes, etc., from the water. Thus, in 1831 a volcano was thrown up in the midst of the Mediterranean Sea, forming a new island called Graham's Island. Being composed of light cinders it was soon cut off by the waves and reduced to a shoal. The three Bogoslov volcanoes of the Alaska-Aleutian chain formed in 1796, 1883, and 1906 are other examples. Such eruptions have occurred repeatedly in the past and their products, mingled with sediments from the land, have been laid down as deposits on the ocean bottom, as seen in many places where the sea floor with these deposits has since been raised and become a land surface. Nor do these volcanic products differ in their essential characters from those which have been described as formed by volcanoes upon the land. It also seems probable that many of the cones formed beneath the sea, and thus protected from erosion, are of great age, even quite old from the geological stand-

point, and have served as the base for coral islands, as previously described, page 184.

Fissure Eruptions. — In several regions outflows of lava have taken place on such a gigantic scale, and cover such widely extended tracts of country, that it is commonly believed they cannot be referred to the outpourings of any volcanic cone, or group of volcanoes. Moreover, the cones from which they might have come are apparently wanting. It is thought that these great lava-floods have issued from fissures in the earth's crust. The result is that broad plains, or plateaus, consisting of successive level sheets of basalt lava, sometimes interlaid with beds of tuff, have been formed. Instances are found in the great lava fields of the Columbia and Snake rivers in the far Northwest of the United States, which cover from 150,000 to 200,000 square miles, and are in places 3,000 feet deep, which are shown on the geologic map accompanying this work; in the so-called Deccan traps of western India which are stated to be 200,000 square miles in extent and to reach a maximum thickness of 6,000 feet; in the north of the British Isles, which in part, with the outlying island groups, appear to have been carved by the sea from a great basalt plateau, which may have extended to Iceland. The level character of these lava sheets is evidently due to the extremely thin liquid nature of the issuing magma, which permitted it to run far many miles before congealing. Thus in Iceland, a lava flow has been traced a distance of 60 miles. It is such outpourings, which occur in other regions as well as in those mentioned, which exhibit to us the grandest effects of vulcanism. It is a conservative estimate to say that, since a comparatively recent geologic period, as much as 500,000 cubic miles of molten material have been transferred from the inside to the outside of the globe by the extrusive process of vulcanism, most of it in the manner here described.

It should be mentioned in this connection that those geologists who have most closely studied the great lava plains of the Snake River do not believe that the molten material issued from an extensive system of fissures, but from various vents, like those of ordinary volcanoes of the quiet type, some situated along the sides of the enclosing mountain chains, others on the plains themselves. The lava craters which mark the site of the vents are, for the most part, so extraordinarily low and broad as to escape detection in a general view, and are only found by closer observation, compare Fig. 164. This is due to the extremely liquid character of the lava which spreads out in streams 50 miles long and many miles wide. Through repeated outpourings of this kind the previous topography was buried and the plains produced. It may be that other lava plateaus, referred to above, were made in a similar way. It will be noticed that the chief distinction between the two views is, that in the one just mentioned, the vents are localized.

Origin of Volcanoes

General Remarks. — So far as regards the nature of volcanoes, the character of their eruptions and of the products afforded by them, their distribution and in some measure their life, we are dealing with ascertained facts. We also know quite clearly the reason for the different kinds of eruption and the varied types of cones. But when we seek to learn the cause and origin of vulcanism we must then consider the depths of the earth itself, about which we know very little. We are led from facts into almost pure speculation, and this should be clearly understood by the student. It is evident that our ideas of the cause of volcanic action will depend upon those which we have concerning the nature of the earth's interior; what has been learned regarding it will be considered in a later place. There are, however, certain phases of it which may be considered here.

Problems of Vulcanism. — Some important questions that arise when we seek to discover the cause of vulcanism may be stated as follows: What is the origin of the *heat* which keeps the magmas in a molten condition? What is the origin and history of the molten *magmas* which come to the surface? From how deep down do these magmas come, and where is the seat of vulcanism? What is the origin of the *gases* and vapors; have they always been contained in the magma, or has it absorbed them from outside sources, and, if so, when and where? And finally, what causes the magma to *ascend* to the surface from depths below and thus give rise to volcanoes? These are fundamental problems, most of which our knowledge, at the present time, is too limited to enable us to solve. Views held regarding them may, however, be briefly stated and discussed.

Origin of the Heat. — At the present time the most prevalent view regarding the source of the heat demanded for the molten magmas is that it is original, the remains of a globe once highly heated, and still intensely hot in its interior. Many, however, do not share this opinion, but regard the heat as due to the gradual contraction and compression of the earth through the force of gravity, a process which should cause a gradual flow of heat outward toward the surface, and by its concentration in particular regions induce melting and the formation of masses of magma. We are not yet in a position to decide definitely between these views.

It has been urged by some that the crushing together of the earth's outer shell through contraction must generate heat on an enormous scale. It is pointed out that such compression and crushing have taken place in the for-

mation of mountain ranges, as we shall see later, and it is inferred that through this process melting has occurred and volcanoes have been made. There are two objections to this view. The first is that volcanoes are often found where there has been no crushing of the outer crust, or at least, not for an immense period of geologic time antedating the appearance of the volcanoes, as at the San Francisco Mountain and other volcanoes on the high plateau in Arizona. The other is that the folding and compression of the earth's crust which makes mountain ranges is a very slow process, and although great quantities of heat would undoubtedly be generated, it has not been shown why it would not be as rapidly dissipated, or transformed in doing chemical work. How could it become accumulated and concentrated sufficiently to produce melting and volcanoes? For, to use an illustration, what we need is not a cask of warm water, but a cupful of boiling water.

Since the discovery of radio-activity, and the researches upon matter which it has induced in these later years, have shown that some elementary substances are disintegrating and breaking down into other substances, as for example, uranium into radium, helium, etc., and radium into helium, lead, etc., with production of heat in notable quantity, it has been assumed by some that changes of this nature are going on within the earth and that in this way the heat necessary for volcanic action is produced. It is pointed out as a proof of this that volcanic regions and lavas show a content of radio-active substances. There is wide diversity of opinion on the subject and, at present, this view has not advanced beyond the speculative stage.

Origin of the Magma. — This is evidently closely connected with the origin of the heat, as just discussed. The prevalent view is that the magma is a remnant of the original molten substance of the globe. Those who hold this view do not, however, necessarily claim that it has always been in a liquid condition. In melting, rock material must expand; if sufficient pressure be put upon it, it cannot expand and, therefore, cannot melt. It is assumed that, with the tremendous pressure reigning in the earth's depths, the material although very hot would be solid, but should relief of pressure come in any place, as for instance, by upward buckling of the earth's crust, or by long erosion reducing the pressure, or by both, then melting would ensue and a body of magma would be formed. A view, once held, was that the lavas are produced by the fusion of deeply buried sediments, but for a number of reasons this idea now receives little credence.

Another theory which has been advanced is that the melting of the rock material is due to the issuing of superheated gases, squeezed out of the deeper, inner portions of the earth's interior by its gradual contraction from cooling. They are supposed to melt the rocks on their upward passage, and thus give rise to the magma and to volcanic action. The difficulty in this view lies in the enormous quantities of gases that would be required to melt rocks and produce

large bodies of magma, and in that the gases under pressure tend to go into solution in the magma and become inert. And so, like the origin of the heat, that of the magma must for the present be considered unsettled.

Origin of the Gases. — In regard to this, opinion has been divided into two classes, one believing that the gases, as indicated in the preceding paragraph, were originally contained in the

Fig. 173. — Pavlof Volcano, Alaska. G. K. Gilbert, U. S. Geol. Surv.

earth, which has been gradually losing them, and another that they have been absorbed by the magma, especially the chief gas, water vapor, from surface waters descending through the crust. The former appears, from several considerations, much the more probable view, and is the one mostly held at this time.

The fact that most volcanoes are situated in, or near, the sea or lakes has been considered a strong proof that the water-gas contained in the magma has been obtained from descending surface waters. But this argument when examined loses its force. The nearness of some volcanic chains to the sea, like those of North and South America, is only relative to the size of the continental masses. Actually they are long distances inland; in South America from 100 to 250 miles and this includes some cones still active—like Cotopaxi—which are not near any inland water body; in North America from 30 to 100 miles or more, and, although these are mostly extinct, it can yet be shown in many cases that when active there was no body of water near them. And the volume of steam, from even small volcanoes at periods of eruption, is sometimes so enormous, as has been previously shown, page 203, that we cannot attribute it to ordinary rainfall or surface water, leaking downward through the rocks. Moreover, if the magma obtains its water from surface supply, it must do so in the very upper part of the crust, since, as already shown, below this the openings which permit of water supply and circulation in the crust are closed up. But several considerations show us that at such shallow depths, far from absorbing water, the tendency of the magma is to get rid of it with great energy and, finally, with terrific force. And if the magma ab-

sorbed such enormous quantities of water and converted it into steam it is difficult to see why it would not be itself cooled off and solidified in the process, and thus fail to reach the surface. Hence, we conclude that certainly the greater part of the water, or its constituents, and perhaps almost all of it, which comes from volcanoes, was originally contained in some form in the magma and brought up by it from great depths. In contrast to the resident surface water of the earth this is known as *magmatic,* or sometimes less happily as *juvenile water.* It appears probable that the other volatile constituents previously mentioned, page 204, are in great part, if not entirely, likewise original.

Cause of Ascension. — What causes the magmas to ascend we do not know, but the fact that the situation of the great volcanic chains is on those belts along which movement and disturbance of the lithosphere (the earth's outer shell of rock) have taken place is a significant one. For these are, apparently, zones of weakness in the lithosphere, and have thus afforded favorable positions for the upward movement of the magma, and its escape to the surface. As will be explained more clearly later, the lithosphere is divided into great blocks, or segments, and these have in times past moved up, or down, with respect to one another. It is often noticeable that where one of these great blocks, measuring hundreds or thousands of square miles in area, has sunk, this has been attended with uprise of magma, outflows of lava, and commonly with volcanic action. Instances are found in the depressed tracts which form the great Rift Valley of East Africa, the valley of the Rhine, the region of the Christiania Fiord in South Norway, and the sunken sandstone area of Connecticut and Massachusetts.

All this suggests that the upward movement of the magma is due in some way to variations of pressure induced by changes of position of the segments into which the lithosphere is divided, although we do not know just how to explain its mode of operation. Some hold that the gradual contraction of the solid earth through gravity, aided by other processes, causes the magmas to rise. The old idea that the earth has a hot, liquid interior, and that the downward pressure of the contracting cold and solid lithosphere forces this liquid out, and thus gives rise to volcanoes, has been completely disproved by a number of considerations, and is no longer held. The independent eruptions of adjacent volcanoes in the same group, and the fact that the lava column in Mauna Loa stands 10,000 feet higher than that in Kilauea, only 20 miles away, are disproofs of this view, while others will be mentioned later.

As to the *seat* of volcanic action, or the point from which the magma may be considered to move on its upward way, we know

nothing. One conjecture we can make is this. From the study of earthquakes, and for other reasons as we shall see later, it appears that the earth consists of an outer shell — lithosphere — whose specific gravity is about 2.7, and this shell is thought to be not of very great thickness, and to change gradually into a denser core. The specific gravity of the earth as a whole is 5.6, hence the inner core must be much denser than the outer rock-shell — the lithosphere. The specific gravity of much of the lavas erupted by volcanoes is not much over 3.0, while that of a large portion is considerably less. Hence it would appear that the material forming the lavas was probably not derived from far within the inner core, and this may determine the seat of action as being not many miles deep.

Hot-Springs and Fumaroles

Introductory. — In the foregoing description of volcanoes it has been shown what an active rôle gases and vapors, especially water vapor, play in their eruptions. But long after a volcano has ceased to be active and has passed into a dormant, or dying, stage these volatile substances continue to issue from its crater, or from its flanks, or even from places in the surrounding country. In the same way thick beds of extruded lavas continue, often for years, to exhale steam and other vapors. And, as we shall show later, it has often happened that large and small bodies of magma have penetrated into the outer shell of the earth, without attaining the surface or forming volcanoes, and these in solidifying, like the lavas, have given off quantities of the same volatile substances which work upward through fissures and pores in the rocks. It is now proposed to describe the class of phenomena produced by such emanations at the surface. They may appear as vapors, or in liquid condition; the former may be considered under the general heading of *fumaroles,* the latter under *hot-springs.*

Fumaroles. — This word, which is derived from a Latin verb meaning to smoke, is applied to those instances where steam and other heated vapors escape with more or less force from fissures, or holes, in the rocks and soils. Although steam is the most common substance, other vapors, such as hydrochloric acid, hydrogen sulphide, carbonic acid, etc., also occur. When the fumaroles give off sulphurous vapors they are often termed *solfataras,* from the Italian word for sulphur. It is noticeable that in the hottest fumaroles the acid gases are prominent; in those less hot, various other volatile compounds, often hydrogen sulphide, which decomposing gives rise

to deposits of sulphur; while as the fumaroles become cooler, or cold, carbon dioxide becomes the chief emanation. Although different regions vary in the proportion and nature of the products exhaled, this general rule seems to hold, not only in time but in space, so that whether one considers the decline of activity at a given center, or travels away from an active one, the change from hot acid vapors to cooler carbonic acid exhalation is noticed. A view of several fumaroles is seen in Fig. 174.

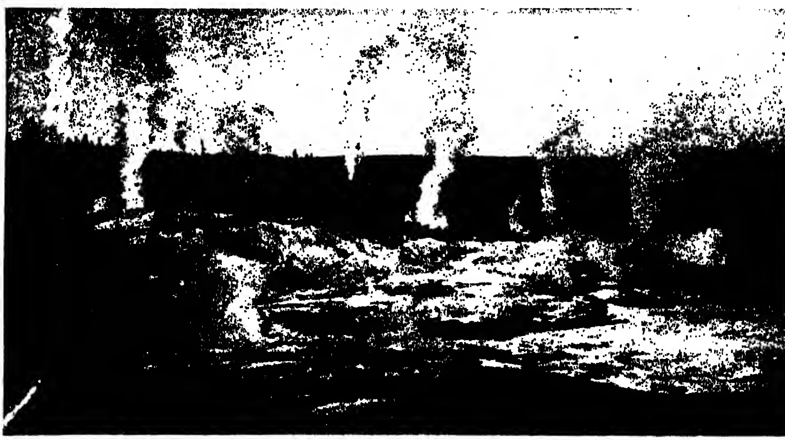


Fig. 174. — General view of the Norris Geyser Basin, showing hot-springs and fumaroles, and the white siliceous deposit of geyserite from them. Yellowstone Park.

The Solfatara near Naples had its last eruption in 1198; since then it has been in the condition of discharging steam mingled with sulphur vapor, and this has given rise to the use of the term *solfataric stage* when volcanoes become quiescent, or are dying. Some of the great cones of the Northwest, like Mt. Shasta, appear to be in a dying solfataric stage. In the Yellowstone Park the solfataric condition is still active and fumaroles abound in many places. Although at times, and in places, the steam given off in fumaroles can be ascribed to magmatic origin, it is often increased, or even surpassed or replaced, by descending surface water being vaporized, either by contact with hot rocks, or by the heated volcanic exhalations. This is probably the case in the Yellowstone Park.

The closing condition in which carbon dioxide gas is given off is found in numerous places where volcanic activity still abounds, and in many where vulcanism has long since died out. It may happen that it issues directly from the ground as a gas spring, and such occurrences are known as *mofets*. Being heavier than air it may collect in still weather in depressions near the vent, and, since it is colorless, tasteless, and odorless, such pools of the gas may prove deadly traps for animal life, by suffocating such creatures as enter them. This is illustrated in "Death Gulch" in the Yellowstone Park, and in simi-

lar places elsewhere. But the gas is far more likely to encounter ground-water on its upward way and thus give rise to carbonated springs, which passing through limestone may deposit carbonate of lime. See page 165. Some hold that the carbon dioxide is derived from the decomposition of the limestone, $CaO \cdot CO_2$, and this may, in some places, and in part, be true, but in other places it can with good reason be referred to a magmatic origin.

Hot-springs. — In volcanic regions hot-springs are likely to occur. We may attribute their origin to different causes; they may be due to descending surface waters being heated by coming in contact with hot rock masses below, or by hot magmatic vapors passing into them, and their returning in this heated condition to the surface. When they occur in active or quiescent volcanic regions, as in the Yellowstone Park, they are probably due to a varying combination of the causes mentioned above. Warm springs, with temperatures up to 120° F., also occur in regions where no direct evidence of connection with volcanic activity or intrusion of magmas can be shown; in this case they are probably deep, or fissure springs (see page 157), and the water has been warmed by contact with rocks whose temperature has been raised by mechanical means, such as crushing, or by chemical changes going on within them.

It is impossible, in certain regions, to tell in the case of hot-springs and fumaroles how much of the water (and steam) is surface and how much is magmatic in origin. It probably varies in different cases. Hot-springs in the rainless arid interior of some deserts have been regarded as mostly of magmatic origin. The proof that magmatic emanations have passed into such waters is found in the presence in them of such substances as sulphur, arsenic, boric acid, etc., in quantities and under conditions which show that they could not have been leached out from the original rocks of the country. In the Yellowstone Park it is probable that the greater part of the water is of surface origin, which becomes heated by contact with lavas still hot, and returns in this condition, but there are good indications that magmatic vapors, once very active, still play a subordinate part.

While there are various types of hot-springs, dependent on their temperature, substances in solution, etc., the most interesting are boiling springs and geysers. Warm carbonated springs depositing travertine have been already described, page 167.

Boiling Springs. — Actively boiling springs are a feature of many volcanic regions. A considerable number of them occur in the Yellowstone Park, especially in the different geyser basins, see Fig. 175. They exhibit various gradations from pools which are hot, but rarely boil, or else quietly simmer, into types which boil strongly and steadily, and some even more or less violently and with somewhat explosive energy, interrupted by short periods of repose. The

latter form transitions to the geysers mentioned beyond. So long as the supply of water is sufficient to enable the spring to have an over-

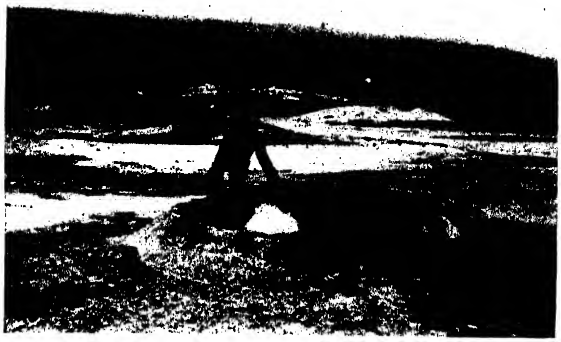


Fig. 175. — "The Devil's Punch-Bowl." A hot-spring boiling in the cup-like deposit of geyserite it has formed. The opening is several feet in diameter. Upper Basin, Yellowstone Park. W. H. Weed, U. S. Geol. Surv.

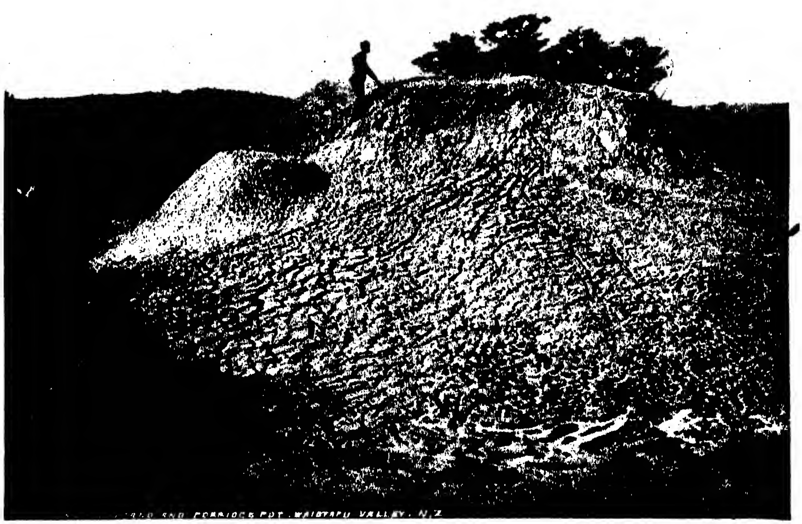


Fig. 176. — Mud Volcano, Waiotapu Valley, New Zealand.

flow it remains limpid, and it usually has a deep blue, or green color, but, if the evaporation through boiling is equal to the inflow, the water is more or less turbid from particles of disintegrated rock, and

eventually becomes a mass of boiling mud. The mud may be white, or variously tinted yellow, red, purplish, or black by oxides of iron and manganese, and such hot-springs are called "paint-pots," "mud-pots," etc. The mud as it increases in amount may become so thick and viscid as to prevent regular ebullition, and, owing to the accumulating steam pressure, action may happen spasmodically and with some violence, the mud being thrown into the air and about the vent, where it collects in considerable masses, see Fig. 176. These are known as *mud volcanoes*, or mud geysers. They usually mark a declining stage of activity in the life of a hot-spring.

Geysers. — This term, from an Icelandic word meaning to gush, is applied to certain hot-springs which at intervals spout a column of

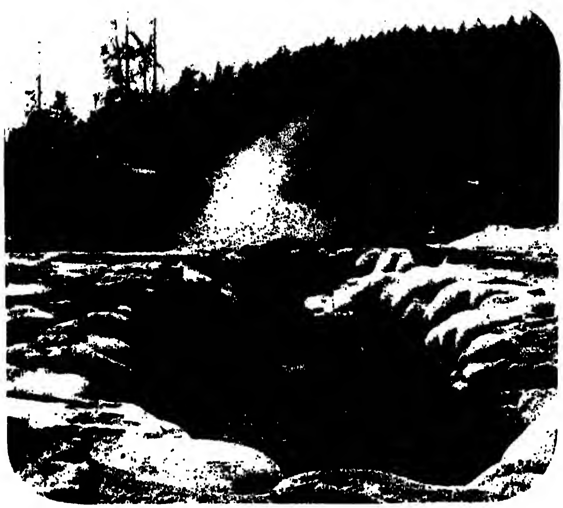


Fig. 177. — Basin of the Oblong Geyser, partly empty, but filling with water after an eruption. The rounded masses are deposits of white silica, geyserite. Yellowstone Park. Haynes photo.

hot water and steam into the air. Depending on the size of the geyser, and its special peculiarities, the column of water may be only a few feet high, or from that up to several hundreds; the eruption may last a few minutes, or several hours; the quantity of water discharged may be small, or be many thousands of gallons; the jet may play steadily and continuously straight up, or be fitful, be composed of minor jets, or be thrown in inclined directions. The interval between eruptions may be a definite one of a number of minutes, or hours, or it may be quite irregular, and several days may elapse between them. Each geyser has in these ways its own

peculiarities. As they are special kinds of boiling springs they are not common and, so far as known, appear to be confined to three regions, the Yellowstone Park, Iceland and New Zealand.

Fig. 178. — Lone Star Geyser in eruption, showing cone of geyserite. Yellowstone Park. Haynes photo.

Fig. 179. — Old Faithful Geyser in action. The jet of water is 100 feet high, at this time. Yellowstone Park.

Some geysers consist, at the surface, of a basin, which may be several feet to a number of yards long, and broad, and rather deep. The sides and edges of the basins are usually beautifully ornamented by the deposits of silica de-

scribed beyond, and terminated at the bottom in tubes or fissures leading to the heated depths below; this type is illustrated in Fig. 177. The tubes and basins are, except after eruptions, filled with water at, or near, the boiling point. In other types the geysers by their deposits have built up mounds, or cones, of silica, from a foot or two to several yards high, which form upward continuations of the pipes. See Fig. 178. Of the Yellowstone geysers the most celebrated, perhaps, is the one known as "Old Faithful," which for many years after its discovery had a very regular interval between eruptions of about 65 minutes, Fig. 179. It is now becoming more irregular. This, and the decline of activity in other geysers, or springs, does not mean any immediate diminution of thermal action in this region, only changes going on in the underground system of pipes and fissures which conduct and supply the hot water. Altogether there are several dozen fine geysers in the park, while the number of hot-springs, fumaroles and thermal vents of various kinds amounts to several thousand. It is a fact not easily explained that geysers have been found only in felsite lavas.

Cause of Geyser Action. — The intermittent eruptive action of geysers depends on the relation between pressure and the boiling point of water, as was pointed out by Bunsen in connection with the great geyser in Iceland. The boiling point of water under the ordinary pressure of the atmosphere at sea-level is 212° F.; increase of pressure raises it, a decrease lowers it. Thus the boiling point at the bottom of a column of water will be raised by the pressure of the superincumbent layer above it; as shown in Fig. 180, it will gradually rise as we follow the tube from the surface downward. If, however, the cavity, or fissure, be large and open, the heated water below will rise, convection currents will be established, mingling the water, so that it will have nearly, though not quite, the same temperature in different parts of the cavity, and a regular boiling spring will result. But if the tube be long, narrow, tortuous, or constricted, convection will be prevented, or restrained, and the water must boil in different levels at different temperatures corresponding to the pressures. Suppose at a point 230° in the figure the boiling point is reached, bubbles of steam are formed, the column of water above is raised a little by the expansion, the bubbles of steam rise into the cooler liquid above and collapse,

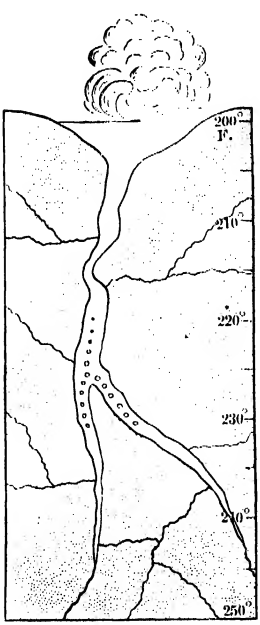


Fig. 180. — Diagram to illustrate conditions necessary for geyser action.

the column of water settles back with jarring, thudding sounds commonly heard before eruption. The temperature of the water will gradually rise until it is just about at the boiling point for each level corresponding to its depth and pressure. Finally, when a sufficient volume of steam is formed in the lower parts, the expansion will cause some of the water in the basin, or cone, at the top to overflow, this lowers the pressure throughout the tube, and the water at each level, being now heated above the boiling point for the diminished pressure, will immediately flash into steam, and a mingled column of steam and hot water will be driven roaring out of the pipe into the air. After the eruption is over the system fills again by inflow of ground-water through the fissured rock, and the process is repeated.

The varied forms of fissures, underground conduits, and water supply account for the peculiarities shown by different geysers. It has been found that adding alkaline substances, such as soap or lye, to the waters of geysers causes some of them to erupt very quickly; this makes the water somewhat viscous and the liberation of steam difficult and rather explosive, leading to sudden lowering of pressure and eruption.

That the source of heat for the geysers and hot-springs in the Yellowstone Park must be quite deeply seated is shown by their occurrence in, and on the shores of, Yellowstone Lake, an immense body of very cold water, below which the rocks must be cooled to considerable depths.

Hot-spring Deposits. — It has been previously shown that where warm springs, especially if they contain carbon dioxide in notable quantity, come up through limestone beds they form deposits of calcareous tufa or travertine. See page 167. But the waters of actively boiling springs and geysers, which occur only in regions of recent geological activity, and in connection with lavas, are mostly alkaline and carry *silica*, SiO_2, in solution, which they deposit as a whitish material, varying from compact to spongy in texture, and known as *geyserite* or, more commonly, *siliceous sinter*. This forms the geyser cones, or is deposited in incrustations, often of great beauty, in and about the margins of the hot-spring and geyser basins. The solutions are dilute, and the rate of deposition is very slow when it occurs only through drying, but is hastened by the action of organisms. Formations of rather considerable size and thickness have been, and are being, made in this way, as seen forming the floor of the basin in Fig. 174. While hot-springs and geysers are not geological factors which are of importance from the magnitude of the results which they achieve, they are yet of great significance in a proper understanding of certain processes, such, for in-

stance, as the deposit of certain ores of metals, and are of wide popular interest.

It has been found by Weed that, as in the case of travertine, page 167, the deposit of silica is very largely due to the secretion of it by low forms of vegetable life, diatoms and algæ, the latter related to sea-weeds, which flourish in the warm and even hot waters. The beauty of many of the pools is greatly enhanced by the rich coloring which these growths add to them. It may be that they represent to us some of the earliest and most primitive types of life which existed on the earth.

Besides silica the hot-springs may form other substances; the waters in some places are acid, and deposit sulphur and alum salts. In other cases sulphides of arsenic and of metals are found, throwing light on the formation of ore bodies.

CHAPTER IX

MOVEMENTS OF THE EARTH'S OUTER SHELL; EARTHQUAKES

Introductory. — Experience and observation show that the outer shell of the earth is not fixed and rigid, but undergoes changes which result in movement of one part of it as compared with another. The evidence is overwhelming that this has occurred repeatedly in the past, and in all those places where it is permitted us to examine the structure of the earth's crust. The movements of the different parts of the outer shell have been differential with respect to one another, and not only up and down, but back and forth in directions tangential to the earth's circumference. The evidence that such movements have taken place lies in the results which they have achieved, and these we shall see and study in detail under the heading of Structural Geology in a later part of this work. Here it is intended to show that gradual and massive movements of the crust of the globe have taken place, not only in the remote but in the immediate past, with results of magnitude, and that they are still continuing. We shall first examine the evidence and then see what conclusions may be drawn from it.

Datum Plane. — It is evident that in order to consider the rate and extent of movement of different areas of the earth's surface, or even to know that it has occurred, we must have some fixed point of reference. For vertical movements the level of the sea immediately suggests itself as a datum plane to which they can be referred. For, if it can be shown that relative displacements of land and sea levels have occurred in any place, it is natural to think that the movement must be that of the land, since the sea, averaging the tides, must maintain a mean tidal level throughout its whole extent. Along coast-lines, therefore, we use the sea surface as the point of reference for vertical movements of the earth's outer shell.

The idea of the fixedness of the sea surface must not, however. be carried too far. As explained on a previous page (90), the ocean does not present us a truly geometric surface, but a warped one. And, as further explained under coral islands, page 188, the sea-level has varied within recent geologic times, first, by the withdrawal of a part of its water, due to its accumulating as ice

on the land, and second, by the restoration of this water to the ocean basins by melting of most of the ice. And also there are reasons for thinking that the ocean has increased in size and depth through geologic time by the constant addition of magmatic waters, as explained under volcanoes. It is also more than probable that, as from time to time the earth shrinks recurrently, with sinking and warping of the floors of the ocean basins, and corresponding possible increase of velocity of rotation, such changes will cause movements of the ocean waters on its surface. Such shiftings are registered by apparent up and down movements of the shores, giving rise to the strand-lines mentioned below. But, since such changes in the ocean are very gradual and general, while the movements of the land we are considering are local, much more rapid, and much greater in degree, we may still for our purposes measure them against the sea-level as a relatively fixed point.

Elevation. — The most striking proofs that upheaval of the land from the sea has occurred consist in the elevation of those features

Fig. 181. — Ancient sea-caves in former sea-cliff at back of elevated beach, showing strand-line. Coast of Fifeshire, Scotland. Geol. Surv. of Scotland.

which we definitely associate with the sea, or its edge, so that they are now inland and high above it. Thus in various parts of the world outcrops of rocks with dead marine organisms, such as barnacles, or other shells, and corals, still attached to them are found high above sea-level, or the rocks are pierced by the tunnels of rock-boring shelled animals (*Lithodomus*) which may still contain their shells. This shows that such changes have recently occurred, while the presence of the remains of shells and other marine organisms as fossils

in the rocks of the highest mountain ranges proves that they have also happened in the remote past.

The classic example of proof of changes in land level is found in the temple of Jupiter Serapis built by the Romans near the seashore in the vicinity of Naples. The three columns left standing are bored by lithodomi to a height of 20 feet above the floor, and their shells may yet be seen in the holes. From this we infer that after the temple was built the land subsided at least 20 feet, or more, carrying the temple into the sea, and that since then it has again risen to an equal amount.

Another line of evidence consists in the elevation of those conspicuous features which the edge of the sea makes in its geologic

Fig. 182. — Elevated strand-lines cut in sandstones and limestones. Straits of Belle Isle, Labrador. Schuchert photo.

work of eroding the land, and which were described in previous pages (97–105.) Thus raised beaches, wave-cut and wave-built terraces, forming level benches of country terminated inland by sea-cut cliffs, the latter often pierced by wave-formed caves, show the elevation of a former sea-margin, Fig. 181. They are often spoken of as a *strand-line,* and commonly appear as a more or less distinct topographic line, or level, approximately parallel to the present shore-line and above it.

Still another line of evidence, of a positive character, is found in what may be termed human records. Thus in northern Sweden the uprise has been under observation for a long period, and has been measured by marks placed on the shore. In one place the elevation was about two feet in a century, but the rate is not everywhere

uniform and it varies also from time to time. All the facts point to the Scandinavian peninsula as having gently risen for a long period, so that its crest in the northern part of Norway is 1,000 feet higher than it once was. Raised strand-lines are a noticeable feature in many northern regions, Fig. 182. Similar facts have been recorded in other parts of the world. Thus the raised strand-lines prove that within a recent geological period the west coast of South America has experienced very considerable elevation, and the process is probably still going on.

Depression. — The evidence that the land, in places, has subsided below sea-level is less striking than that of elevation, but not less convincing when fully understood. We must here look for a different kind of evidence, for the fact that the sea has encroached

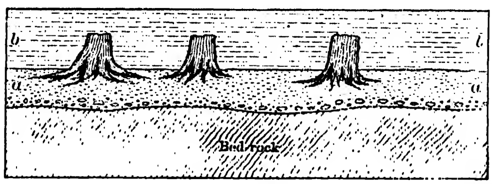


Fig. 183. — Diagram showing submerged forest. *a*, old forest soil with stumps standing in it; *b*, marine deposits of silts and sands.

upon the land is not in itself a proof of subsidence, since this may be due to simple landward erosion, as previously explained, page 101. Rather we must seek for the submergence of features which are definitely characteristic of land surfaces. Such are found, for example, in submerged forests, and in buildings or other structures of mankind, now standing in the water. Increasing depth of average water-level over well known rocks or reefs in harbors is another proof.

Submerged forests are found at various places along the Atlantic coast-line from Maine southward. The diagram, Fig. 183, shows the stumps still standing in the forest soil, while above are the marine deposits covering them up. It is clear that this could occur only in situations, such as protected nooks and corners of estuaries, sheltered from the waves of the encroaching sea, which would otherwise have swept away the forest soil. Sometimes the tree stumps are now uncovered and may be seen standing up on the sea-bottom in the water. Submerged peat-bogs which have become tidal flats are rather common and tell the same story. Borings in the deltas of great rivers, such as the Mississippi and the Ganges, as described beyond, show that the subsidence may continue for long periods. All the collected evidence goes to show that the Atlantic seacoast from Maine southward has gradually sunk within the last geologic period; whether it is still sinking is a matter about which geologists have not yet reached agreement.

Drowned Valleys. — The most impressive evidence of subsidence of the land, when its significance is understood and appreciated, is seen in the irregular coast-lines produced by the drowning of valleys, with production of bays and estuaries. This has in part already been discussed, page 104, and Fig. 80. The seaward extension of river channels, such as the Hudson, across the submerged continental shelf for long distances, points also in the same direction, for manifestly these great trenches, sunk in the sea-floor, could not have been cut while the area was covered with water, but only by river or glacial action, or both, when it stood at a higher level and was a land surface.

Subsidence and Deposit of Sediment. — It is a commonly observed fact that in many parts of the world, where heavy deposits of sediment are being laid down by rivers in the sea adjacent to the coast, subsidence of the ocean bottom is in progress. This is noted in the deltas of large rivers, like that of the Mississippi. Borings through them show a great depth of deposits. Sometimes these are marine, sometimes fresh-water in nature, as shown by the shells which they contain, alternating with beds of peat and buried forest-growths. These facts show that subsidence has been going on for a long period, and not at an even rate, but as an interrupted process, whose variations permitted land, fresh-water, and marine deposits to be formed. Not only is this occurring in the present, but, as we shall see later, it has happened in many places in the past, so that enormous thicknesses of deposits, up to 40,000 feet, or even more, have been laid down in particular localities, which have been afterwards raised and exposed to observation. Such great thicknesses of sediments are associated with mountains, as we shall see later, for elsewhere they are much thinner. Since the products of land waste are chiefly deposited close to the shore, see page 106, and, as we cannot imagine a depth of 40,000 feet at the edge of the land, we are forced to believe that subsidence must have been occurring along with the deposition, to permit accumulations of such thickness of the sediments.

It has been a view of some geologists that the subsidence is caused by the load of accumulated sediment. They consider the earth's crust to be in such a state of equilibrium, *isostatic balance* so-called, maintained by the yielding of plastic material below, or the rocks being forced under pressure to act as if plastic, that where the crust is lightened by erosion it will rise, and where it is loaded by sediment it will sink. But it is to be noted that should elevation occur in one area of the crust and subsidence take place in an adjacent one, erosion would tend to cut down the rising area and fill up the subsiding one. The mere fact that shifting of material occurs is not in itself a proof that it is the cause of the change of levels; it may be the effect of such change

rather than the cause. Probably it is both cause and effect. The subject will be considered more fully in another place.

Evidences of Elevation or Depression Inland. — We can hardly assume that movements of the shell involving changes of level are confined to the sea-coasts; they must also occur inland, in the interior of the continents. That this has happened during the past is plainly shown by several lines of evidence: for example, by the bodily sinking of tracts of land, such as occurred at New Madrid, Missouri, in 1811-1812, and by the behavior of antecedent rivers in maintaining their courses through upwarps and thus forming canyons, as previously discussed, page **76**. But there are also other facts that prove changes of level have taken place very recently inland and are, perhaps, still going on. This is shown by the tilting of lakes, as illustrated in the diagram, Fig. **184**.

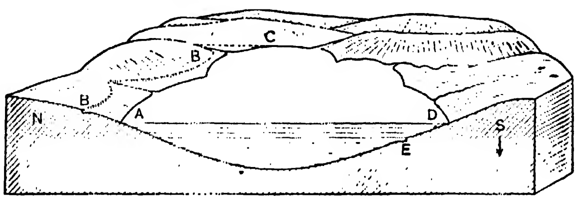


Fig. 184. — Showing tilting of lake basin. *AD*, present lake level. *BB*, raised shore-line disappearing under lake at *C*. Land has been depressed to south (*S*) and on this side the former shore-line, *E*, has been drowned.

The Great Lakes present one of the best examples of this. To the northeast of them the land appears to have risen since the retreat of the great ice sheet in a huge low dome or shield. Since they lie on the southwest side of this area of doming they have been tilted to the west and south. On the northeast side the old strand-lines are several hundred feet above the present water-level, and slope toward it as they are followed west and south. Since the lakes discharge to the east, the raising of their outlets has caused them to enlarge, expanding them to the west and south. The process, with modifications, has continued down to the present, with the drowning of river mouths on the south and west sides of some of the lakes (Erie and Superior), and their conversion into estuaries, and is probably still going on.

Warping movements downward may also be shown by the conversion of a part of a river valley into a lake. Thus downwarping has converted a portion of the upper course of the Ottawa River into a long narrow body of water, known as Lake Temiskaming. It occupies the site of a glaciated valley and is deep and narrow.

Another line of evidence, which so far has not been much studied, or well established, consists in gradual changes in scenery, brought about by slow warping effects of the earth's crust, like the appearance of a distant object, such as a building, rock, or hilltop, over the crest of an intervening ridge from some well determined spot, whence in previous years it could not be seen. A number of such changes are reported, but examination has thrown serious

doubt upon their validity. Since they must take place very slowly, and the work of erosion must also be taken into account, until proper photographic and surveying records have been long established, no real dependence can be placed upon them.

Classification of Movements. — In a geologic sense the shell of the earth is never quiet or at rest, but it is always undergoing slow motion; in one place apparently motionless for a period but in another slowly rising, in another gradually subsiding. During one epoch the continents are heaving upward and the seas retreat from their borders, at another they are sinking and the oceans advance and eat their way inland. At times these motions have become more energetic and certain belts of the earth's shell have been crushed together, both longitudinally and transversely, with folding and fracturing and the rising up of mountain ranges, as we shall see more in detail in a later place. All such movements of the outer shell, whether of continental masses, or in mountain making, whether of folding or fracturing, or dislocation of one part with respect to another part, whether upward or downward, or by horizontal thrusting or stretching, are comprehended under the general term of *diastrophism*, and the forces producing such results are spoken of as *diastrophic*. For the sake of convenience also, when diastrophic forces affect and move the continental masses, they are termed *epeirogenic*, from the Greek *epeiros*, a continent; when concerned in making mountain ranges, *orogenic*, from the Greek *oros*, mountain, and *gen*, producing.

These diastrophic movements are probably all to be referred to the same general cause, but it is useful to distinguish between different phases according to the results achieved. Thus, in addition to the terms epeirogenic and orogenic, gradual warping movements of the land surfaces, such as those taking place about the Great Lakes, have been called *bradyseisms* (from the Greek *bradus* and *seismos*, meaning slow earthquake).

Intermediate between the epeirogenic forces concerned in the making and moving of continents and ocean basins, and the orogenic ones giving rise to mountain ranges, are those which elevate or depress great blocks of the outer shell. The movement is essentially in a vertical direction. The upward movement of such areas on the continents has given rise to plateaus, such as those of the Colorado and of Thibet, while the downward one has yielded depressed tracts, like the great Rift Valley of East Africa with its contained lakes. In the ocean basins the submarine plateaus and the "deeps" (see page 91) point to similar movements and results. The areas thus raised or depressed do not move as units, but are broken into great blocks whose movement is attended with more or less dislocation, the result of which we shall have occasion to consider

later. All the movements which tend to produce changes in the earth's surface are often spoken of as *deforming,* and the results achieved by them as *deformations.*

Cause of Diastrophism. — When we endeavor to account for the various movements which the earth's outer shell has undergone, and is still undergoing, it appears that we can find for them an *immediate* cause, but not at present an *ultimate* one. Concerning the immediate cause there is quite general agreement of opinion, and it is held to be due to the *unequal contraction* or shrinking of the earth, taken as a whole. There is a great body of proof which shows that the outer shell of the earth has undergone this contraction and that it is probably continuing; through this the surface is gently warped up or down, and at times there has been more energetic crushing in certain belts and areas. The proof of this we shall study in detail in a later part of this work.

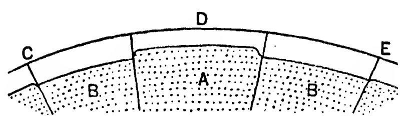


Fig. 185. — Diagram of deforming movements. *A* and *B, B* have sunk from the original surface *CDE*, but *B, B* more than *A*, so that the latter appears to have risen. *A* is a horst, *B, B* are graben.

But concerning the ultimate cause, the reason why the earth should contract, why it should do so in an irregular manner, and how the shrinkage causes diastrophism, there are, indeed, many opinions but, as yet, unfortunately not much real knowledge; what is known and the most important views that are held will be discussed in a later place; before taking them up we will next consider certain results of these movements, which are not only of interest and importance in themselves, but, as it has recently appeared, have taught us some valuable facts regarding the character of the earth's interior, and seem destined to teach more as their study continues. We refer to earthquakes, whose consideration follows in the next section.

In the preceding discussion of diastrophism reference has been made in a number of places to upward and downward movements. These should be understood to be relative terms, the position of one area with respect to its surroundings. For it is possible that in the shrinkage of the earth, each of the areas and our datum plane, the ocean level, are all moving towards its central point, but that some move faster, or more, than others, and thus cause these relative changes. See Fig. 185. Those areas which stand at a higher level, or apparently rise, are often spoken of as *positive* elements of the shell, in contrast to which the depressed tracts are termed *negative* ones, terms

whose significance will appear when we study the geography of the world in past geologic times. Areas like *A* in the diagram, Fig. 185, are known as *horsts,* those like *B, B* as *graben,* from the German, the one meaning an elevation, the other a trench, or trough.

The main positive elements of the earth's crust are, or have been, continental areas, the negative ones are the deep ocean basins. The continental areas are again broken into smaller tracts, which are subordinate negative and positive elements, according to their motion with respect to one another; it is these that are commonly distinguished as *horsts* or *graben.*

Earthquakes

Introductory. — In the preceding section it has been shown that in a geological sense the earth's shell is undergoing constant movement on a large and massive scale. In what we may term a present sense it is constantly subjected to relatively small and often rapid motions. These may arise from a great variety of causes, and, ordinarily, they are not perceived by us, though they may be detected by suitable instruments. When they occur as tremors which we can distinctly recognize they are called *earthquakes.* These are not only interesting in themselves as geological phenomena, but are of such great importance to humanity, on account of the loss of life and great destruction which they frequently entail, that they have been made the subject of wide-spread and continued investigation. As a result there is perhaps no field of geological inquiry in which greater progress has been made, especially in recent years, and some of the more important facts and conclusions are here presented. The study of earthquakes is known as the science of *seismology,* from the Greek *seismos,* an earthquake.

Cause of Earthquakes. — An earthquake is a trembling, or undulatory motion, in the more or less elastic rock-shell of the earth communicated to it by an impulse or shock of some kind, as a bowl of jelly might be set in vibration by a smart tap on the side of the containing vessel. The shock or impulse is evidently the cause of the earthquake, and the question arises, what is the origin of such shocks? The evidence shows that they may arise from several causes, most of which must be considered of minor importance compared with one major source, which appears to give rise to all great earthquakes.

One minor cause is found in violent volcanic outbursts, like that of Krakatoa in 1883 and of Bandaisan in Japan in 1888, but earthquakes produced in this way are light in intensity and quite limited in extent. Moreover, many outbursts are not attended by any shocks, or but extremely feeble ones, like that of Mont Pelée in 1902. It used to be thought that volcanic action was an important source of earthquakes and this idea is frequently revived; but the careful comparison of the two phenomena, especially in Japan, has shown

that there is no necessary connection in occurrence between heavy earthquakes and volcanic eruptions.

Another minor cause may be found in the sudden caving in of subterranean cavities, due to the yielding of the roof to the weight of superincumbent rock masses. This is most liable to happen in limestone regions, since this rock is apt to be removed in solution by underground waters, as previously explained, page 162. It is possible, as has been suggested, that the earthquakes which in 1811 devastated the lower Mississippi valley, especially about New Madrid in southern Missouri, were partly due to this cause, though the area affected is too extensive and the effects of the earthquake shocks produced were felt to too great distances for it to have been more than a minor one.

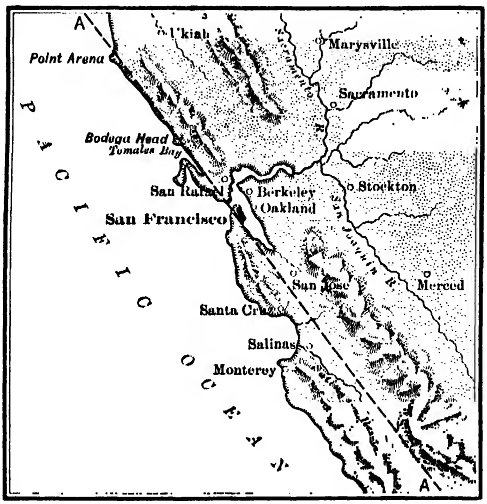


Fig. 186. — Map of a part of California, showing the position and extent of the fault-line, A–A, movement along which produced the earthquake of April 18, 1906.

It has now been rather definitely settled that the main cause of earthquakes, especially the heavier ones, is the jar given the earth's shell by the sudden forming of a fracture in its outer portion, or, perhaps, a sudden slipping, or displacement, along the walls of an already existent fracture. The upper part of the earth's shell is divided by rifts into blocks, both great and small; such fractures probably die out below at a depth of twelve miles, or thereabouts, where the overlying weight exceeds the crushing strength of the rocks, though temporarily, at the time of formation, they may penetrate more deeply. Above this the blocks may adjust themselves to the contraction of the earth as a whole by settling down, and by movement along the walls of the rifts. Fractures along which dislocation has taken place are called *faults* and, as we shall see later, such faults are a matter of great importance in structural geology. The scale on which such phenomena take place is very great; the

fault along which abrupt movement caused the great earthquake in California on April 18, 1906, has been traced, with only two or three

Fig. 187. — Trace of the fault fissure concerned in the California earthquake of 1906. G. K. Gilbert, U. S. Geol. Surv.

interruptions, a distance of 600 miles and displacement occurred along at least 250 miles of it; it is known as the San Andreas Rift. See Figs. 186 and 187. This is, however, exceptional and distances of 40–50 miles are more common. The fractures, if already existent, are not necessarily open, their walls are pressed tightly together, and perhaps in places healed by deposited material. A sudden forced motion, even of only a few inches, along ~~such~~ fractures, with friction and perhaps rupture, where the masses involved are so tremendous is quite sufficient to generate a shock which would produce a disastrous earthquake. The motion is commonly vertical, and may amount to several feet and even yards, see Figs. 187, 188 and also Fig. 277, but lateral and oblique movement is also liable to occur; thus the horizontal displacement on the sides of the fault-line in the California earthquake of April, 1906, was from 8 to 20 feet, as shown by the separated ends of fences, etc., see Fig. 189, while the

maximum vertical dislocation was not more than from one to three feet.

The most recent view of the cause of earthquakes, according to H. F. Reid, is not that the shock is caused by the bodily slipping movement of a great block of the earth's shell in mass, but rather by the sudden fracture of the rock along a line in an area which has long been under gradually accumulating strain. He states the causes and effects as follows.

The fracture of the rock, which causes a tectonic earthquake, is the result of

Fig. 188. — Displacement, or fault, along a great fissure which produced a heavy earthquake in Japan in 1891, at Midori in the Neo Valley. K. Ogawa, photo.

elastic strains, greater than the strength of the rock can withstand, produced by the relative displacement of neighboring portions of the earth's crust.

These relative displacements are not produced suddenly at the time of the fracture, but attain their maximum amounts gradually during a more or less long period of time.

The only mass movements that occur at the time of the earthquake are the sudden elastic rebounds of the sides of the fracture towards positions of no elastic strain; and these movements extend to distances of only a few miles from the fracture.

The earthquake vibrations originate in the surface of fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in the rock.

Effect of Shock. — The student must carefully bear in mind the difference between cause and effect in earthquake phenomena; thus in Fig. 188 the displacement shown is not the result of an

earthquake, but the cause of one. The effect of the sudden movement along a fault line, or the forming of a new one, is that vibrations are sent outward in the earth from that place, and these are the earthquake, as it is perceived at a distance. Within a certain

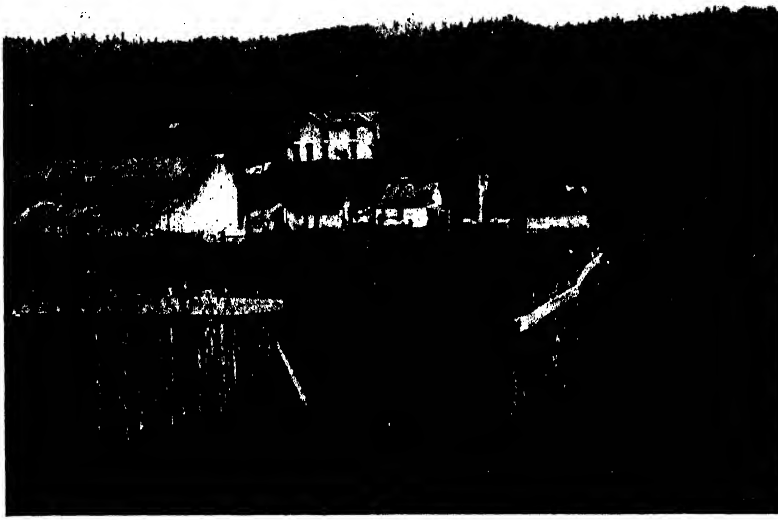


Fig. 189. — Horizontal displacement, or shove, without appreciable vertical change, as shown by the separated parts of the fence. One is looking perpendicularly toward the plane of the fissure. California earthquake of 1906. G. K. Gilbert, U. S. Geol. Surv.

zone, on either side of the fault line, or on both sides, the destructive effects observed in the demolition of buildings, etc., may be chiefly due to the sudden shift in the ground, especially if this takes place horizontally; at increasing distances from this line the vibrations are more and more the cause of the different things which may happen. Thus the earthquake is propagated as a series of waves in the earth, as in an elastic body. When these emerge at the surface the ground is thrown into very short, rapid vibrations, which even in severe earthquakes have a range of only a few inches. The waves

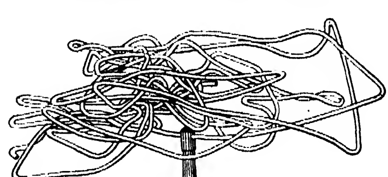


Fig. 190. — Wire model showing path traveled by a particle of matter during an earthquake; after Sekiya.

along the surface move at a rate of about two miles per second. The motion is not only back and forth, but also up and down, and the path described by an individual particle may be very complicated, as illustrated in Fig. 190. The nature of the elastic waves transmitted through the earth and what they have taught us will be discussed in another paragraph.

It used to be thought that earthquakes were generated from a point at some depth, say from two to six miles, below the surface and this was called the *focal point*, or centrum. The point immediately over this on the surface was called the *epicenter*. This latter point was determined by drawing concentric closed curves, called coseismal lines, on a map of the region through points of simultaneous arrival of the waves, as indicated by observatories, clocks, etc. See Fig. 191. By other mathematical methods the distance below the epicenter of the focal point was calculated. These methods led to discordant results for a given earthquake, and eventually to the discovery that there might be several epicenters situated in a line, or that where earthquakes habitually occurred in a given region the epicenters were situated on this line. Further investigation showed that these were fault lines and this led to the present understanding of their cause, as previously stated. Thus the former ideas of a focal point, of its depth below the surface, etc., have in large measure lost their significance.

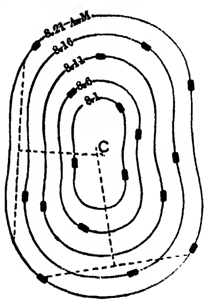


Fig. 191. — Map of coseismic lines.

Recent Examples. — On August 31, 1886, the city of Charleston in South Carolina was visited by a severe earthquake which killed and wounded a number of people and did great damage to buildings and other structures. The shock was distinctly felt as far away as Chicago, a distance of 800 miles. It has been suggested that this was caused by the sudden slipping seaward of vast masses of sediment accumulated on a descending coast-line, but the attendant phenomena leave little doubt that like most other earthquakes it was due to the settling and adjustment of shell blocks.

On May 3, 1887, a tremendous earthquake occurred in the province of Sonora in northern Mexico. It was felt over the greater part of New Mexico and Arizona, but as these were then very thinly settled regions little damage was done. The fault occurred at the base of a mountain range which was uplifted in places twenty feet.

In 1899, a great earthquake took place in southern Alaska. As the region is mostly uninhabited it passed almost without notice at the time. Studies which have since been made show that considerable alterations in topography took place at the time of its occurrence, especially about Yakutat Bay. Marked changes were also induced in the great glaciers of this region (page 128) by the shattering of the ice and by snow slides from the mountains. See Fig. 277.

On April 18, 1906, occurred the great earthquake in central California which has been previously mentioned. The loss of life, from various causes may have reached 1,000; many towns and cities were greatly damaged; but the chief destruction took place in San Francisco. The city, damaged by the shock, was in

great part destroyed by a resulting conflagration, which could not be checked because the pipes carrying the water supply were laid across the fault-line, and the displacement cut them in two.

Fig. 192. — Destruction caused by earthquake vibrations, Stanford University, Cal., April, 1906. W. C. Mendenhall, U. S. Geol. Surv.

In August, 1906, the coast of Chile was visited by a severe earthquake, which did great damage in Valparaiso and other places. The number of persons killed was estimated at several thousand. After-shocks continued for a long time while readjustment along the fault surface was going on. The west coast of South America is noted for its earthquakes, in connection with which notable elevation of the coast-line has occurred.

On January 14, 1907, a heavy earthquake happened at Kingston, Jamaica, with destruction of property and changes in the coast-line and in the harbor, due to faulting.

The greatest disaster of this kind in modern times occurred on Dec. 28, 1908, when Messina and Reggio, cities on the narrow strait which separates Sicily from the mainland of Italy, were completely destroyed by a terrific shock. It is estimated that possibly 200,000 lives were lost in this frightful catastrophe. The region has repeatedly suffered from this cause in previous times; it is one in which crustal readjustment is constantly going on.

These are only a few examples out of many that might be selected. Scarcely a day passes that shocks are not recorded from some part of the world by the earthquake observatories.

Seismic Belts. — Observation shows that although earthquakes occur in all parts of the world they are most likely to happen in

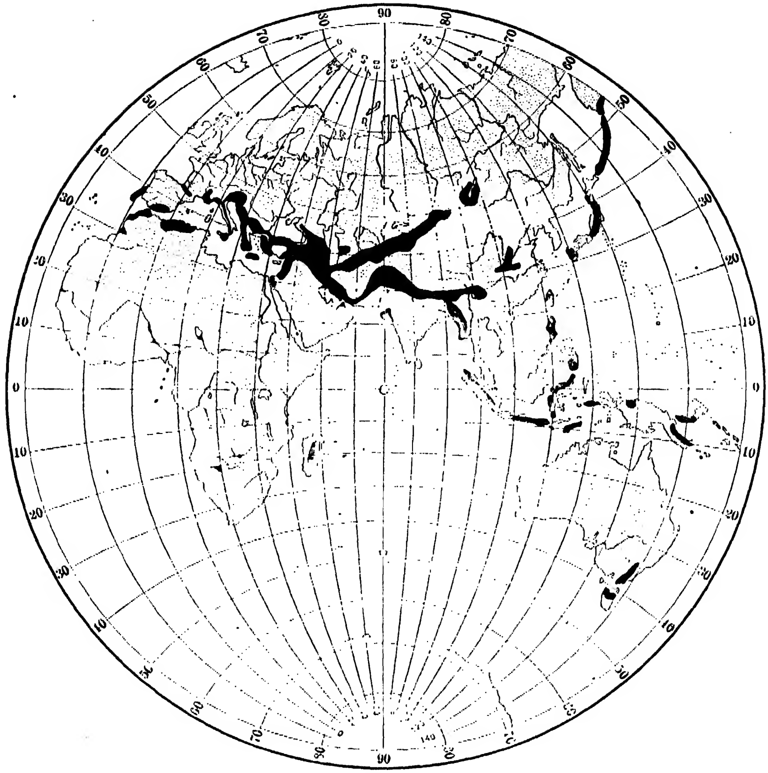


Fig. 193. — Map of seismic belts in the Eastern Hemisphere. On S. L. Penfield's stereographic projection.

certain well-defined tracts, which lie in what we may call the great seismic belts. These surround the earth as zones roughly in the direction of great circles which cross at an angle of nearly 70 degrees.

One belt follows the western coast of North and South America, the Aleutian Islands and the island groups along the eastern coast of Asia and thus defines the Pacific Ocean. The other includes the Mediterranean, the Alps, the Caucausus, the Himalayas and so on into the East Indies. These are shown on the accompanying maps in Figs. 193 and 194. It will be noticed that in a general way they coincide with the great volcanic belts previously described, page 204, and thus tend to show that there is a common cause for both sets of phenomena. It is also a notable fact that where these belts lie along the continental coasts, as in North and South America and on the eastern coast of Japan, the land descends very sharply, with-

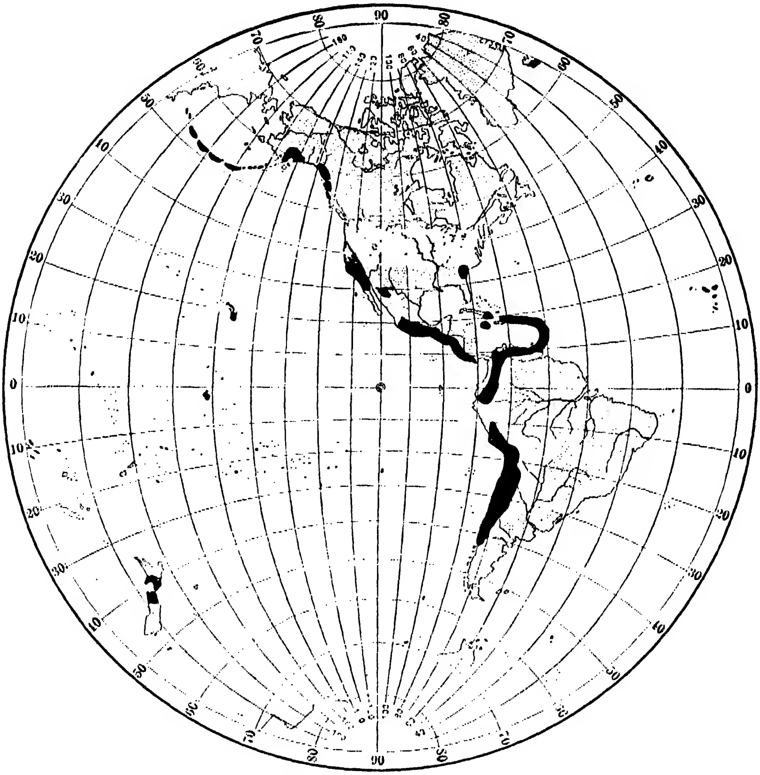


Fig. 194. — Map of seismic belts in the Western Hemisphere. On S. L. Penfield's stereographic projection.

out any broad intervening shelf, to the depth of the ocean. See page 83. These slopes are the edges of concave tracts of the ocean floor, from 100 to 300 miles wide, which border the continents and which appear to be sinking; while, conversely, the bordering land areas appear to be rising, and in long stretches have been elevated as mountain chains, as we shall see later. These are the belts or zones of weakness in the earth's crust where the stresses and strains incidental to the contraction of the earth are being constantly relieved by movements, and in which, therefore, earthquakes are continually recurring.

It is often thought that certain regions are practically exempt from danger of earthquakes because no real disaster has happened in them since they have been settled and cities have sprung up. Yet in New England, for example, in the 230 years following its settlement over 230 distinct earthquakes have been recorded, an average of one a year, though probably none have been of the first

magnitude. Where the shocks are frequently recurrent and slight, the danger of a large movement and heavy shock seems less; where quiet has long reigned in a seismic belt, the shock which eventually comes is apt to be severe, suggesting that the strain in the one case is constantly eased, in the other cumulative. It has also been noticed that a heavy shock in one seismic belt seems to be followed, not long after, by one in a very distant belt, rather than by one in neighboring regions, as if, locally, the stresses and strains were eased. This is illustrated by the Valparaiso earthquake which followed soon after the San Francisco one in 1906.

Submarine Earthquakes; Tsunamis. — What is stated in the foregoing discussion of seismic belts suggests that a large part, possibly the greater part, of earthquakes takes place on the ocean bottom, on the descending sides of the deeps. That they do occur beneath the sea is shown in several ways, such as the shocks communicated to vessels on the surface above, and by the rupturing of submarine cables. And with the sensitive instruments by which, as will be shown later, it is now possible to record distant earthquakes,

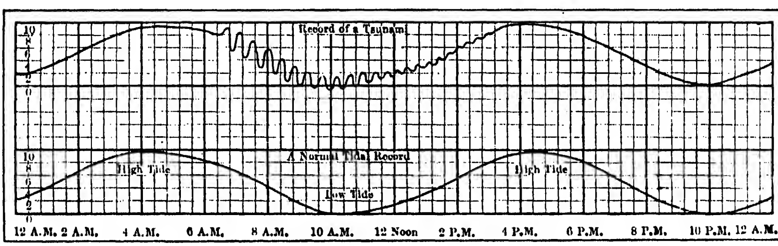


Fig. 195. — Record of tsunami by tidal gauge. Vertical lines represent time spacing on the paper, driven horizontally by clockwork. Horizontal lines show height in feet as recorded by the rising and falling pencil of the gauge.

and determine their place of occurrence, many are found to happen beneath the sea. The most important thing which these submarine earthquakes cause is the huge wave which they may generate in the sea. Such waves have long been known under the title of tidal waves, a misleading name since they have no connection with the tide; they are now generally called *tsunamis*, from their Japanese name, by seismologists. They may be of immense size, from 100 to 200 miles from crest to crest, and at the point of origin 40 feet high. They are so broad that in the open sea, unlike wind waves (see page 88) they would not be perceived; but if, on approaching the coast, they are still of considerable height they may pile up in huge breakers and, sweeping far inland, cause enormous damage and loss of life.

Lisbon in 1755, Japan in 1854 and in 1896, Peru in 1868, suffered well-known instances of great and disastrous tsunamis, the number of victims in some cases

being 20,000. These vast waves are felt over whole oceans and move with tremendous speed, from 300 to 500 miles per hour. Those from Japan have crossed the Pacific in nearly 12 hours, and are registered by tidal gauges. At such distances their height may be only a few inches; but the ebb and flow of from 15 to 30 minutes, like small subordinate tides on the top of the regular tide, would be registered as wavy lines by the instrument. See Fig. 195. It is these records which enable us to determine the size of the wave since they give the time of oscillation; the speed between distant points being known, the size = velocity × time of oscillation.

It has been supposed that these waves were due to the uplifting or depressing of an area of the sea bottom by the shock, but Reid has recently shown that it is much more probable that they are caused by the elastic rebound of the crust which follows when it has been gradually strained to such an extent that a line of fracture finally and suddenly occurs, with quick movement on either side of the break, as in the California earthquake of 1906.

Recording Earthquakes; Seismographs. — Very delicate instruments have been invented, called seismographs, which record the tremors due to distant earthquakes, and the study of these records has led to important geological conclusions. The principle upon which such instruments are now constructed is simple; if a heavy mass of metal be suspended like a pendulum, owing to its inertia it will remain for a long time at rest when the shock arrives, while the earth vibrates beneath it. A point or pencil of some kind is secured to the suspended weight, while under it, on a bed-plate rigidly attached to the earth, is a paper or other medium suitably prepared to record the motions of the point which lightly touches it. If the earth oscillates beneath the suspended pencil a series of lines will be drawn on the vibrating paper. If the paper, instead of being made fast, be a strip continuously carried along by clockwork the pencil when at rest will draw a straight line upon it; when vibrations of the earth occur the line will be broken and will oscillate sinuously from one side to the other. See Fig. 197. Such a record is known as a seismogram.

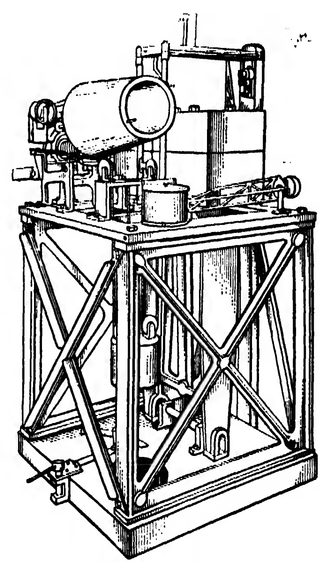


Fig. 196. — Seismograph with astatic pendulum, Wiechert's model.

While in principle, a modern seismograph is simple, in construction it is a rather complicated instrument (see Fig. 196) since it is arranged to record not

only horizontal motion in two directions, East-West and North-South, but also the vertical motion as well. It is from such records in three directions that the wire models shown on page 247 are constructed. Since the intervals of time are marked on the moving paper, the instrument records the time of arrival of the shock and also the duration. The directions of diversion of the markers from their regular paths show also the direction from which the shock has come.

Seismograms. — The study of seismograms of distant earthquakes has led to the discovery that the main shock is preceded by smaller quick vibrations which are recorded when the seat of disturbance is greater than 1,000 kilometers (about 620 miles) from the recording station. These are known as the preliminary tremors.

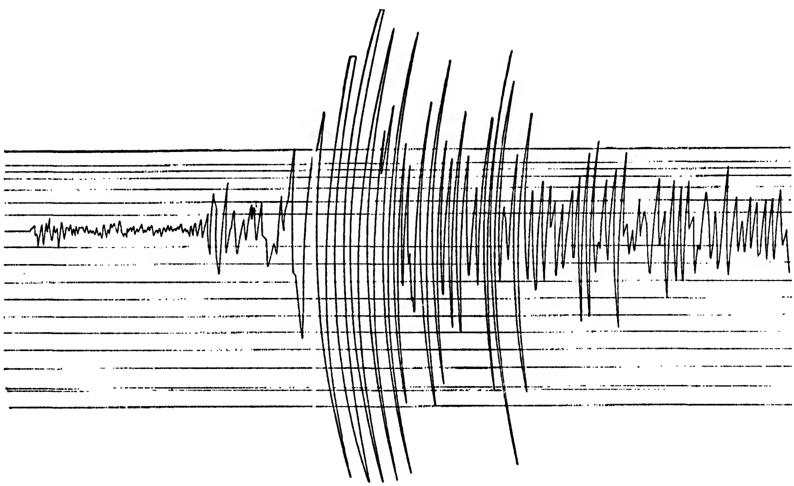


Fig. 197. — Record of the earthquake in Messina on Dec. 28, 1908, as shown by a seismograph in Göttingen, Germany, over 1000 miles distant.

Thus a normal seismogram has the characters seen in Fig. 198. From a number of considerations it is now agreed that these preliminary tremors represent the shock which has come by the quickest path *through the earth,* that is, in the general direction of a chord from the seat of disturbance to the recording station, whereas the large vibrations (see Fig. 198) represent those waves that have traveled by a longer route over the surface circumference. The time between the arrival of the preliminary tremors and that of the main shock is proportional to the distance of the place of disturbance, and the following rule has been worked out which gives roughly the distance from the seat of shock: the duration of the *first* preliminary tremors in minutes (and fractions of minutes), less one, is the distance of the place of disturbance in thousands of kilometers (1,000 kilometers = 621 miles approximately).

It is now generally agreed that the first preliminary tremors, coming through the earth, are longitudinal waves of compression, the direction of vibration of a point being in that of the line of propagation, that is, to and fro, whereas in the second preliminary tremors coming through the earth the wave is one of distortion, with the directions of vibration transverse, in a plane normal to the path traveled. On the surface these waves are "rocking" ones.

The large surface waves passing around the world in the direction opposite to that between the points of the seat of shock and the recording station, and thus through their antipodes, have also been detected by the seismograph.

If the distances from three recording stations are known, then by drawing

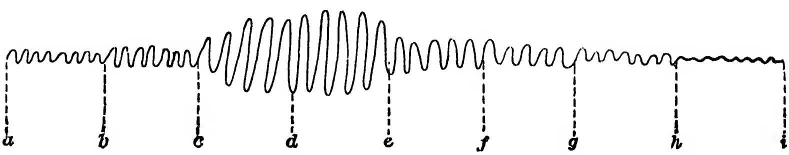


Fig. 198. — Seismogram of distant earthquake; *ab*, first preliminary tremors; *bc*, second preliminary tremors; *ce*, main shock; *fh*, later phases; *hi*, tail (after Omori).

circles on the globe with these distances as radii and the stations as centers, the place of disturbance may be determined by the intersection of the three circles. In this way the place of shock has been located in some instances on the ocean floor.

Geological Deductions from Seismograms. — The fact that the preliminary tremors, which are supposed to travel through the earth, arrive at distant points so long a time ahead of the main shock, cannot be explained alone by the shorter path traveled. The time interval shows that they are also propagated at a much greater rate of speed than the vibrations traveling in the outer shell of the earth. The deduction from this is that they move in a denser, more elastic medium which enables them to gain speed as they go. Moreover, the concordant results in different directions show that inside of the outermost layer, which we know is heterogeneous in composition, the earth is homogeneous, or regularly arranged around its center in structure, or, if non-homogeneous, the heterogeneous parts are relatively so small and numerous that different paths of considerable length through them give the effect of uniformity. Moreover, the average velocity increases with the distance of the recording station, thus the rate of transmission along

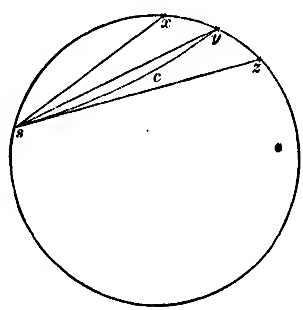


Fig. 199. — Paths of transmission of earthquake shock through the earth. *S*, seat of shock; *x*, *y*, *z*, recording stations.

sz, Fig. 199, is greater than along *sy*, which in turn is greater than along *sx*. Reid has calculated from the data afforded by the California earthquake that, at the depths below the surface given, the velocity of the first preliminary tremors is as seen below:

Depth below surface, miles	Speed in miles per second
0	4.5
272	6.0
612	6.9
1,225	7.8
1,968	7.9

These results show not only that velocity increases with the depth, but more and more slowly as the depth increases, and this would seem to indicate that the density and elasticity of the earth increases with the depth down to a certain region. Seismographs of sufficient accuracy and delicacy have not yet been so generally installed that data concerning earthquakes at distances as great, or greater, than one-third of the earth's circumference are sufficiently reliable for us to draw very definite conclusions from them. The chord connecting the ends of the arc of one-third the earth's circumference (120°) cuts the earth's radius at its middle point, and thus it is this outer shell, 2,000 miles thick, concerning whose density and elasticity the seismographs have so far given us the most information.

From the fact that the rate of speed increases with the depth, in the outer shell, 2,000 miles thick, it follows that the quickest path of wave transmission from the seat of shock to a distant station in this portion of the globe will not be a straight line, as from *s* to *y* in Fig. 199, along the chord of the arc, but will be a curved line concave upward, somewhat as the line *scy*. In other words, by following this line the waves gain more in time in entering more elastic layers than they lose in distance, hence seismologists generally assume that the path followed by the waves making the first preliminary tremors at a distant recording station is a curved one. This is of some importance because, assuming the path to be a straight one and noting the fact that the preliminary tremors do not generally show in seismograms unless the distance is greater than 1,000 kilometers, the deduction has been drawn that there must be a sharp boundary between the outer rocky heterogeneous shell of the earth and the inner homogeneous core, and that, since the chord of an arc of 1,000 kilometers at its middle point is 12 1/2 miles below

the surface, this must be the thickness of the outer layer. Others assuming a curved path have made the thickness as much as 800 miles. But Reid has shown that the probable reason why the preliminary tremors do not show in the records of 'near' earthquakes is that instruments are not generally sufficiently delicate to record and distinguish them as distinct from the principal shock, until distance produces time intervals great enough to be recognized.

We have not yet knowledge enough of the earth's interior, nor are the data yielded by the seismographs from earthquake shocks, though promising, sufficiently accurate and comprehensive for us to fix the limits of the outer shell of the earth, if, indeed, there can be said to be a very definite one. This subject will be further considered in a later chapter.

Geological Effects of Earthquakes. — There are several geological effects from earthquakes, but they are, comparatively speaking, of minor importance. The earth is often ruptured by the passage of the wave with the formation of fissures, which may be of some depth. A more important one is the starting of landslides and avalanches in mountainous regions, through the jarring of the earth. A variation in the flow of water from springs, or the forming of new ones, has also been observed.

Much more important are the movements of the shell blocks which cause earthquakes, but as previously remarked, these are the cause and not the effect of the shocks; these movements have been considered and the results which they produce are treated under Structural Geology.

DIVISION II. STRUCTURAL GEOLOGY

CHAPTER X

GENERAL STRUCTURE AND PROPERTIES OF THE EARTH

In the foregoing pages there has been given a general description of the various *processes* which have been, and still are, modifying the outer portion of the earth, the part which is directly open to investigation and study. In considering these agencies we have, to some extent, been led to notice *the material* upon which they operate, and *the results which they have achieved*, but this has been done only in so far as was necessary to understand the principles involved, and therefore, only in a superficial way. It is now appropriate that these materials and results should be more fully treated, and we shall commence by considering the earth as a whole, in relation to its general structure, and the properties it is known to possess, and in stating briefly the ideas which are held regarding the nature of its interior.

The Earth and Its Neighbors. — The earth is one of a group of planets which revolve around a common central orb — the Sun. Some of these, like Jupiter, are much larger than the earth, some like the asteroids, or minor planets, are much smaller; some are much nearer the sun, others farther away. The group has very nearly a common plane of revolution about the sun, as suggested in Fig. 200, and this fact is held to have an important bearing on the origin of the system. The path of the earth about the sun is not a circle, but an ellipse, one of whose foci is the sun; the deviation of the ellipse from a circle is relatively small; the average distance of the earth from the sun is nearly 93 millions of miles, it is about $1\frac{1}{2}$ millions of miles nearer, or farther, from the sun according to its place in its elliptical path. The eccentricity of the ellipse varies during long periods of time, from 100,000 to 200,000 years, and at a maximum the earth may be over 13,000,000 of miles nearer the sun in summer than in winter.

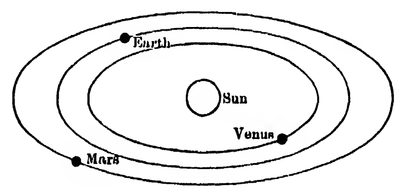


Fig. 200. — Planets revolve about the sun in nearly one plane as suggested by three of them.

As we shall see later, this has been held by some to be a cause sufficient to produce great climatic changes and glacial epochs. Besides revolving about the sun, the earth, as is well known, is spinning on its own polar axis, each revolution in 24 hours giving rise to day and night. This axis is not perpendicular to the plane of the earth's orbit, but inclined to it at an angle of about $23\frac{1}{2}°$, and this gives rise to the seasons, summer and winter, alternately in each hemisphere.

The earth is a very insignificant fraction of the universe as the latter is known to us, and for that matter so is the solar system itself. Nevertheless, throughout the vast extent of the universe, with its myriads of suns and solar systems in various stages of development, the same general physical laws, which we know upon the earth, appear to govern. Gravity operates in the same manner; light is transmitted everywhere by the same kind of vibrations; the spectroscope tells us that the same chemical elements are found in distant suns and meteors as on our earth. Nor do the meteorites which we gather in our journey through space, and which appear like the disrupted fragments of former worlds, bring to us substances strange to the earth. There appears, consequently, to be a unity of law and a uniformity of material throughout space, and we consequently feel justified in assuming that facts and reasoning derived by astronomical study of the other heavenly bodies may be logically applied in our study of the earth.

Form of the Earth. — The earth is not a true sphere, but a spheroid, flattened at the poles, and the polar axis, or diameter, on which it revolves, is about 26 miles less than an equatorial one. This oblateness, or bulging at the equator, is the form naturally assumed by a revolving mass, which, like a liquid, is free to assume its shape in response to the forces acting upon it; a mass of liquid in space, free from outside forces, would become a sphere through the power of its own gravitative attraction; if revolved it would bulge at the equator and flatten at the poles, and the amount of distortion would depend on the speed of rotation. It is held that the degree of distortion of the earth stands in direct relation to its mass and rate of rotation.

It is argued by some that this is a proof that the earth was once in a liquid condition, but this is not a necessary conclusion. For if the forces tending to distort the earth were greater than the rigidity it possesses, the earth would yield to them, no matter whether it were liquid, or solid throughout. Moreover, the ideas of liquid and solid, and the notions of rigidity which we attach to them, when referred to the vast bulk of the earth, and the enormous forces of several kinds which govern its condition, have relatively little meaning.

It has been suggested that the rate of rotation has been gradually lessening, or in other words the day has been growing longer, during geologic time. The reason advanced for this is that the tides, sweeping across the oceans in a direction opposite to that of rotation, on being checked by striking against the continents, act as a brake which tends to retard the rapidity of revolution. If this be

admitted, and also the view that the form of the earth is in relation to the of rotation as mentioned above, it would follow that its surface area has been decreasing throughout geologic time. For, if the speed of rotation should lessen, the amount of oblateness would also decrease, and the earth approach a more spherical shape. But since the sphere is that form in which a given mass of matter has the smallest surface area, the latter would also decrease. But in regard to this view it has recently been demonstrated by Chamberlin and others, after careful computations, that the amount of retarding effect of the tides on the earth's rotation is so small that it must be considered as a negligible factor. The geologic evidence is also decidedly against the view that during geologic time there has been any definite change in the form of the earth through decrease in its oblateness! The evidence will be considered later under mountain ranges.

Others hold, however, that the earth has been contracting, and, since a contracting body tends to revolve faster, this should counteract any retarding effect of the tide. This effect when studied geologically also seems negligible, in that the amount of shrinkage during the period recorded by geological events has been too small to cause such a change in the rate of rotation as should affect the form of the earth.

Density and Rigidity of the Earth. — The density, or specific gravity of the earth, as determined in several ways, is about 5.6. The density of the outer shell is about 2.7, and this indicates that the interior must be different in constitution from the outer part. If the outer shell is relatively thin, the density of the inner core need not be very different from that of the earth as a whole. If, on the other hand, the outer portion of the earth be considered rather thick, a considerable fraction of the earth's radius, then the density of the interior must be proportionately higher. The indications given by the study of distant earthquakes seem to favor the view that there is no definite crust, and that the density increases gradually with the depth.

The *rigidity* of the earth, or its capacity for resisting deformation, and its *elasticity*, by virtue of which it tends to resume its original shape when deformed, are relatively high, as much as one and a half times that of hard steel, and perhaps more.

The rigidity of the earth is shown by its capacity to resist the deforming tendency produced by the attractive forces of the sun and moon. We see the effect of these on the watery envelope of the earth in the production of tides, and the fact that the earth retains its shape in spite of them, is the strongest proof we have that its interior is not in a liquid condition, in the sense in which we use that term on its surface, as was once firmly believed. For, if the earth, or any considerable portion of it, were a liquid covered by a relatively thin shell, we should have interior tides and consequent displacements of the outer crust, which is not the case. Thus, whatever may be the condition of the interior, it possesses that degree of rigidity which we associate with solid bodies.

Its highly elastic nature is shown by the speed and uniformity with which it

transmits the compressional waves of earthquake shock in any direction through its mass. Compared with the vast size of the globe, these shocks are relatively very feeble, and that they should be transmitted such great distances through it is a striking testimonial to the elastic nature of its interior. That the earth transmits distortional waves of earthquake shock, as explained under earthquakes, is also a proof that its interior is not liquid, or, at least, that it possesses the physical quality of elasticity we associate with a solid, and not with a liquid.

It has been suggested that the greater elasticity of the interior of the earth is due to increasing density, caused by the tremendous pressure of the superincumbent material. It is calculated that the pressure at the center is equal to 3,000,000 atmospheres, or 45,000,000 lbs. per square inch, and, of course, it varies with the depth; at the surface it is one atmosphere, at one-fifth the radius, or about 800 miles down, it is over 500,000 atmospheres, or 7,500,000 lbs. per square inch. We can scarcely conceive that such pressures would not cause an increase in density, especially towards the center, and the transmission of earthquake shocks, as mentioned above, indicates that the difference in density and elasticity is gradual, and, perhaps, due to increasing pressure alone, but it may also depend on a difference in the kind of material forming the inner and outer portions.

From the high specific gravity of the earth, and its magnetic properties, it is thought by some that the interior consists largely of iron, and the fact that most of the material which comes to us from space in the form of meteors is composed of this metal, is held to strengthen this view.

Interior Heat of the Earth. — This subject has been mentioned under volcanoes, and may be now further discussed. The interior heat manifests itself directly in two evident ways, by the uprise and outflow of molten magma and heated vapors, and by the increase of temperature as one descends into the earth. Indirectly its presence is also indicated by certain changes and phenomena, to be discussed later, which have occurred in the rock-shell of the earth, and for which the presence of heat has been necessary.

The rise of temperature as one penetrates the rock-shell varies in different regions. The average is stated as 1° F. for every 60 feet, but this means little from the practical point of view, for the increment may be much greater or less than this. In the region of the copper mines of Michigan, which are nearly 5,000 feet deep, it is about 1° F. for every 100 feet, while in mines in other places it may be almost five times as rapid.

In the relatively shallow depths reached by mines it may be much influenced by local conditions, thus in some the rapid increment noted may be due to chemical processes, such as the oxidation of ores containing sulphur, while the slow rise of temperature noted above in the Michigan copper mines may be partly induced by the greater conductivity of the rocks of that area. Also these rocks are very old ones geologically, and it has been noted that in old rocks the rise is slow, perhaps 100 feet or more to 1°F.,

whereas in young volcanic rocks it may be comparatively rapid, 28 feet to 1°F. In Great Britain it is stated to vary from 34 to 130 feet. It is often a matter of great importance in mining and tunneling operations: thus some mines have been found difficult and expensive to work owing to the great heat encountered, and it is thought that on this account mining below certain depths would not be feasible. In the making of the great railway tunnels which traverse the Alps this factor has been a serious one; the surfaces made by connecting points of equal heat increment as one goes down, and known as *isogeotherms*, are not necessarily parallel to the general surface of the earth, but more or less irregular, and rise in the interior of mountain chains, so that in a horizontal tunnel one encounters greater heat as the tunnel proceeds inward. See Fig. 201. Thus, although the economy of operation on lower grades would more than offset the cost of driving longer tunnels at lower levels, the interior heat prohibits their construction below certain levels, and in one recently constructed it was so great there was fear for a time that the undertaking would have to be abandoned.

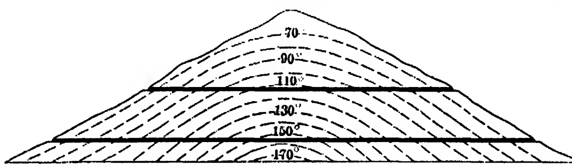


Fig. 201. — Illustrating the rise of heat in the interior of mountains, and the difference in the difficulty of constructing high and low level tunnels.

If the heat increased regularly 1° F. for every 60 feet of descent there would result a temperature of 3,600° F. at 41 miles; this would liquefy rocks at the surface, especially if the melt contained water vapor, and it is probably as high a temperature as that of the hottest lavas, which attain the surface, or higher. As shown by volcanic phenomena we can reasonably assume that there are regions within the earth where the temperature attains a height of at least 3,600° F. = about 2,000° C., but beyond this all is unknown and a matter of speculation. The depth of 41 miles is also an assumption, for it is based on the rate of 1° F. for 60 feet; whereas the average rate, after some depth is attained, may be quite different.

If one assumes that the rate of heat increase mentioned above is uniform to the center of the earth, the temperature would there be about 350,000° F., but for several reasons this seems highly improbable. The outermost shell of the earth is a poor conductor of heat, the inner portions with higher density should be good conductors; if we should imagine that at some depth below the surface it is relatively hot, say 2,000° C., the fall-off in heat, or rate of decrease, in the outer part towards the surface would be rapid; while in the other direction from this point towards the interior we should expect the rise in temperature, with increasing density and better conduction, to be relatively slow.

Nature of the Earth's Interior: Origin of Heat. — Our ideas of the cause of the interior heat of the earth must of necessity be closely connected with those regarding the nature of its interior, and these in turn lead to speculation concerning the origin of the earth itself. The last subject is historical in character and is, therefore, properly treated in the second portion of this work. In their bearing on the question of the interior structure of the globe and its heat, some prominent views which have been advanced are, however, of importance, and may be briefly considered.

a. Nebular hypothesis. The view which has been long, and is still widely held, is that the earth, formed as the condensation of a portion of a vast glowing cloud of extended vapor, was once a molten mass, whose outer shell through cooling solidified as a solid crust, while the interior, though excessively hot, also solidified through the enormous pressure of the superincumbent layers; and that between the two, is either a zone of liquid, because the pressure there is not sufficient to solidify it, or one of material solidified by pressure, but so hot that, if in any way the pressure is sufficiently diminished, it will liquefy. According to this view the heat of the earth is primitive; what it now exhibits is that remaining from its former condition. It may be remarked in regard to this hypothesis that the supposition of a liquid layer is no longer tenable in view of what has been learned concerning the rigidity and elasticity of the earth, as previously shown; if the general hypothesis with the second alternative be accepted, the zone where liquefaction will ensue, if pressure be sufficiently relieved, becomes of geologic importance and will be further considered elsewhere.

A modification of the above hypothesis consists in the assumption that the increase of heat is so great that towards the center matter cannot remain in either the solid or liquid condition, but, being heated above the critical point, it must be in the gaseous form and, on account of the enormous pressure, contracted to a density far beyond that of solids at the surface. By reason of this condensation the substances are supposed, although in the gaseous condition, to possess so great an internal viscosity, or resistance to flowage, that the mass has a rigidity sufficient to meet the demands which, as has been shown above, astronomical considerations impose. It is inferred that certain facts concerning the transmission of earthquake shocks favor this view. It is to be noted that, if the core increases so greatly in density, the outer shell of low specific gravity must be of considerable thickness in order that the average density of the whole earth may be maintained at the proper figure of 5.6, and this appears to agree with the results of seismic investigation, previously stated. Under the conditions and with the properties assumed, the term "gaseous" seems hardly applicable. With the enormous pressures reigning at the center of the earth, the condition of matter must be very different from anything known at the surface, whether it be moderately, or enormously hot. Under sufficient pressure and proper conditions the rigidity of solid metals at the surface of the earth breaks down, and they undergo through mashing a flowage like liquids. But the resistance to flowage is greater than would be the rigidity at the earth's surface. Under such pressures it would seem as if substances would be

resolved into a condition neither solid, liquid, nor gaseous, as we know them, and which might be, indeed, a fourth state of matter; the condition they might assume on relief of pressure may depend on the temperature.

b. Planetesimal hypothesis. In recent years serious objections have been advanced which throw doubts upon the validity of the nebular hypothesis in the form previously stated and another hypothesis has been propounded in the endeavor to meet them. The statement of this is found in the second part of this book; it is sufficient to say here that the earth is regarded as having been built up gradually by the infall and accretion of relatively small solid bodies termed "planetesimals." Through the enormous pressures exerted under the influence of gravity, contraction has ensued, and gaseous matters have been expelled, giving rise to the atmosphere and surface waters. The contraction is thought to be the source of the interior heat; in the interior core, where the contraction is greatest, the most heat develops, and this flows outwardly to an intermediate zone. The latter is held to receive heat faster from the interior than it loses it by conduction to the outer crustal zone; as a result melting ensues, and the liquid material, by the forces to which it is subjected, works its way upward to the surface and, along with the escaping gases, gives rise to volcanic phenomena. The escape of heat through volcanic agencies regulates the temperature of the intermediate zone, and prevents any notable mass of it, beyond relatively thin volcanic threads, from becoming liquid. This hypothesis has been recently advanced; it apparently meets the objections raised against the former one; whether it will encounter new difficulties of its own, time alone can tell.

c. The *radio-active* properties of matter have still more recently been appealed to as a source of the earth's interior heat, as has been previously mentioned under the causes of volcanic energy.

We have learned that in the disintegration, or breaking down of certain elements, such as uranium and thorium, into other elements, such as radium and lead, and in the further disintegration of radium into helium and by-products, relatively enormous quantities of heat are developed. Furthermore, radioactivity is found to be a widely spread property of rocks, especially of the igneous ones. That a part of the earth's interior heat is due to this cause is unquestionable; recent investigations would seem to indicate that it may be entirely so. It also seems most probable that radium, and the heat which it produces by its disintegration, are confined to a shallow zone of the exterior, but a few miles in depth. It is stated that investigation in the Alpine tunnels has shown that the rate of heat-increase is proportional to the radio-activity of the rocks. While we are not yet in a position to see clearly the full significance of the matter, it seems probable that this conception of the part played by radio-activity may lead, as it is further investigated, to ideas concerning the physical state of the earth's interior, and the cause of its different energies, which are quite different from anything expressed in the foregoing discussion.

Isostasy. — This term (from the Greek, meaning equal standing) is applied to a theory of the physical condition of the globe in which it is conceived to be in such a state of relative plasticity, either through the viscous yielding of material, or the forced flow of solid matter, such as rocks, through gravitational pressures, that

from circumference to center each column of substance composing it, like the spokes of a wheel, is in a sort of hydrostatic equilibrium with every other column. That is, columns of equal diameter have the same weight. But as some parts, like the continents, stand at a higher level than other parts, like the deep ocean basins, they must do so because the material composing them, in the top part of their column, is deficient in density compared with the other parts below them in level. See Fig. 185. As the outer shell of the earth is composed of heterogeneous substances, and through erosion and other processes constant shifting of material is going on, the theoretical condition supposed above is not perfect, and the earth is constantly tending to bring itself into isostatic equilibrium by the slow flowage of material below, through the stresses produced by gravity. According to this view the continental masses are the result of a kind of relative flotation of lighter material below their surfaces and, therefore, project, whereas the ocean basins are depressed because of the denser material below them.

Aside from the general geologic evidence that those areas, where lightening of the crust by erosion is taking place, are rising ones, while those parts of the sea-floor where rivers are laying down heavy deposits are sinking (see page 239), this theory receives some additional support from the results of surveys made by the U. S. Government to determine the form and curvature of the United States, and from pendulum experiments to ascertain in different regions the force of gravity. These show that there is a general isostatic balance between the continents and ocean basins, but that the large mountain ranges are probably not in isostatic equilibrium.

It has been calculated that at a depth of about 70 to 100 miles isostatic compensation is complete, and that the adjustments take place in this upper shallow zone. The variation in density between the highest large area on the continent, the Colorado Plateau (reaching to 11,000 feet), and the greatest ocean depth of the Atlantic (18,000 feet), which have been investigated, is actually small, only about 3 per cent less, or greater, than the normal one at sea-level, and less than the difference between different kinds of rocks. This seems in agreement with the general observation that the rocks composing the continental masses are of lighter specific gravity than the basaltic ones which the mid-oceanic volcanoes usually contain, and which latter are our clue as to the nature of the material underlying the ocean floors. It should be said, however, that, although the experimental work mentioned shows that some sort of compensation is probable, the exact results which it was thought to yield have been considered to be very doubtful. Further work in this direction is needed before we shall be able to consider the geologic evidence fully supported by the mathematical results obtained by physical measurements.

It may at first thought seem contradictory to what has previously been stated concerning the rigidity of the earth, that it should yield to the comparatively small loadings and unloadings which isostatic equilibrium would

imply, or, in other words, that it is so plastic and so weak a structure. But the student must remember that all such terms are relative and that the earth, while adjusting itself to minor differences of load and level, may yet be sufficiently strong to resist the stresses which astronomical considerations show the sun and moon impose upon it.

The theory of isostasy may prove of importance in enabling us to understand certain geological processes, but, as it has not yet been sufficiently investigated to receive general acceptance, and certain facts which appear opposed to it have not yet been explained, it should be regarded at present as tentative.

Relief Form of the Earth

General Features. — The irregularities of the earth's surface, or its relief, divide naturally into major and minor groups. The former are the continental masses and ocean basins, while the minor groups consist of mountains as opposed to interior valleys and basins on the land, and of islands as contrasted with the deeps on the sea-floor. The mean height of all the lands above sea-level

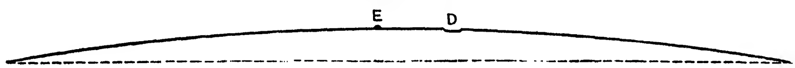


Fig. 202. — Mt. Everest in comparison to the size of the globe. Part of the arc of a globe with radius of one foot is shown; on this Mt. Everest, *E*, would be about $\frac{1}{60}$ of an inch high. *D*, in a similar way, shows the greatest depth of the ocean.

is about 2,400 feet, of North America about 2,000 feet; the average depth of the sea about 13,000 feet. The highest elevation of the land, Mt. Everest in the Himalayas, is 29,000 feet; the lowest known point in the ocean, in the Pacific, is 31,000 feet deep. This makes the greatest difference in relief 60,000 feet or nearly 12 miles. Relative to the size of the globe its relief is extremely small and it is, therefore, comparatively smooth; see Fig. 202 which shows its greatest roughness. The features of the land are divided into *plains*, such as the Atlantic coastal plain; *plateaus*, such as that of the Colorado; and *mountains*, like the Appalachians extending from Canada to Georgia and Alabama. In regard to the grouping of the relief forms of the earth, certain facts are of interest and importance. The continents have a tendency to consist of interior basins with mountain chains as coastal rims, while the ocean basins often reverse this with deeps near the continents, and submarine ridges, or up-swells of the bottom, in mid-ocean. And in a number of cases the highest and most important ranges on the edge of a continent border the important deeps in the ocean floor, as for instance the Andes in South America and the partly submerged mountain chain which forms the Japanese islands, and is the real eastern

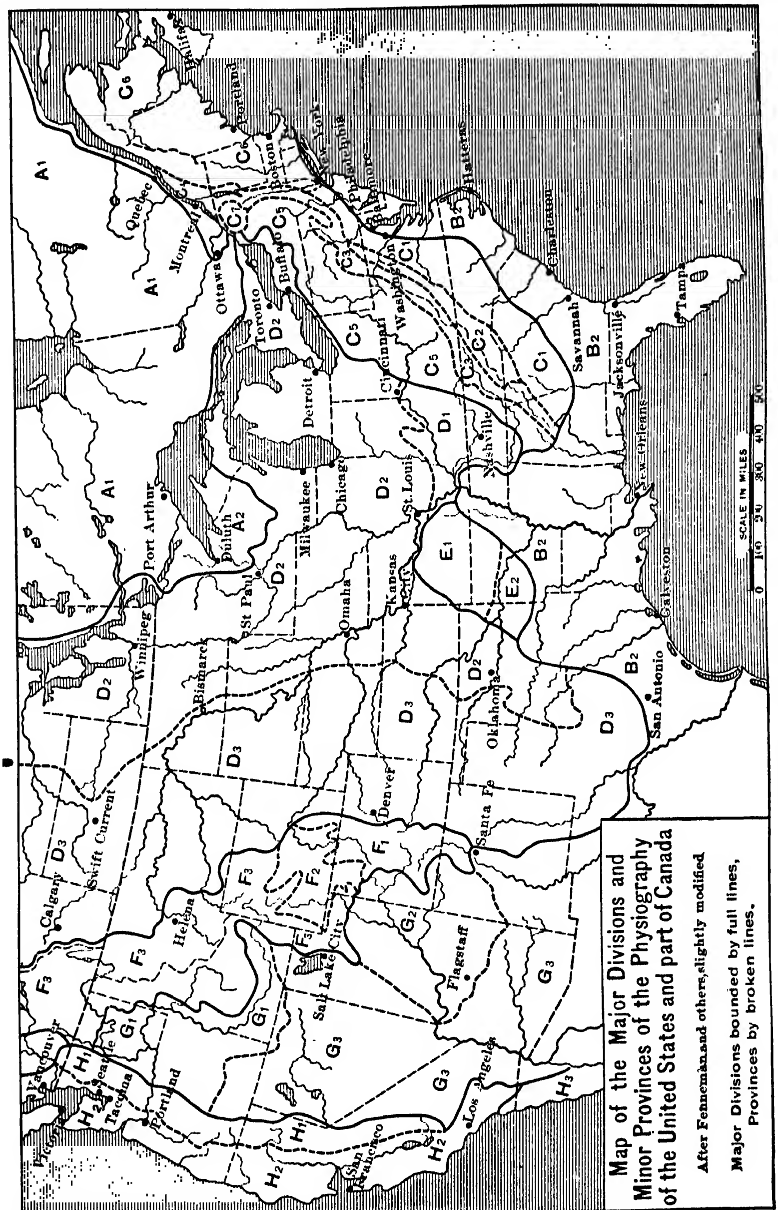


Fig. 203. — Chief physiographic divisions of the United States and part of Canada.

border of the continent of Asia; close to these the ocean floor descends to great depths. See page 250. This is not meant to imply, however, that mountains are found only at the continental edges, for they may extend in a wide zone far into the interior, as in western North America, or form systems crossing a continental mass, as in Asia.

Character of North America. — North America is the most typical of the continents in that it is bordered by mountainous tracts on either side and contains the great basin of the Mississippi and its tributaries in the interior. The following broad features of the continent, and especially of the United States, the student will do well to bear in mind, as they enter into many of the discussions of its geology. On the east and south the continental shelf rises from the sea as the Atlantic coastal plain, and this meets the base of a rugged mountainous tract of country, which stretches from Alabama into Canada and is known as the Appalachian Highlands; it includes the Appalachian Mountains. This gives way to the interior basin whose higher western part forms the Great Plains. The lower part of the basin is the Central Lowland, from which the Mississippi descends through the Coastal Plain. To the west the Great Plains give way to the long series of north and south ranges which form the western back-bone of the continent and are grouped under the name of the Rocky Mountain System. Between this and the Pacific Mountain System, which makes the western rim of the continent and consists of the Sierra Nevada and Cascade mountains with the Pacific border lands, lie the Great Basin and the Colorado and Columbia plateaus. These relations and other minor ones are seen on the map, Fig. 203.

The physiographic divisions of the United States and southern Canada recognized by physiographers are exhibited on the map, Fig. 203. They are classified into major divisions, shown by letters, and minor provinces, indicated by numbers. Their names are given in the following list:

Major Divisions	*Provinces*
A. Laurentian Upland.........	A_1, Laurentian Plateau. A_2, Superior Upland.
B. Atlantic Plain.............	B_1, Continental Shelf (submerged). B_2, Coastal Plain.
C. Appalachian Highlands.....	C_1, Piedmont Province. C_2, Blue Ridge Province. C_3, Appalachian Valley Province. C_4, St. Lawrence Valley. C_5, Appalachian Plateaus. C_6, New England Province. C_7, Adirondack Mountains.

Major Divisions	*Provinces*
D. Interior Plains	D_1, Interior Low Plateaus. D_2, Central Lowland. D_3, Great High Plains.
E. Interior Highlands	E_1, Ozark Plateaus. E_2, Ouachita Province.
F. Rocky Mountain System	F_1, Southern Rocky Mountains. F_2, Wyoming Basin. F_3, Northern Rocky Mountains.
G. Intermontane Plateaus	G_1, Columbia Plateaus. G_2, Colorado Plateaus. G_3, Great Basin and Range Province.
H. Pacific Mountain System	H_1, Sierra-Cascade Mountains. H_2, Pacific Border Province. H_3, Lower California Province.

The Outer Zone of the Earth; Rocks

As has been shown in the preceding discussions, we know but little regarding the interior of the earth; chiefly it is the outer zone of rock of which we have extensive and positive information; upon it we live and exert our activities; we penetrate into it for fuels of various kinds, for metals, water, building material, and other things, and for reasons upon which the physical side of modern civilization depends. A thorough knowledge, therefore, of the component parts of this shell and its structure is of the highest importance. The component parts are rocks, and we shall begin our inquiry by a study of the different kinds of rocks and the varied modes in which they occur. For the most part, as we shall see, the causes which have produced them have been described in the foregoing part of this work; we are here concerned with the results.

Definition and Classification of Rocks. — The word rock, geologically speaking, means the material composing one of the individual parts of the earth's solid shell. In ordinary usage a rock means something hard and firm, but, geologically, a rock may be composed of a soft substance; thus a bed of clay or volcanic ash may be considered a rock, as well as a mass of granite.

According to their mode of origin, and the position of the masses with respect to the earth's shell, and to each other, rocks are divided into three main groups; the *sedimentary,* or bedded rocks, formed by the deposition of sediments, chiefly by water (and to some extent by air); the *igneous* rocks, made by the solidification of molten material; and the *metamorphic* rocks, produced from the preceding groups by certain processes which have wholly, or partly, destroyed

their original characters and replaced them by new ones, so that they may be conveniently considered in a separate group.

Thus we have three groups:

I. Sedimentary Rocks, sediments deposited by water or air.
II. Igneous Rocks, consolidated molten masses.
III. Metamorphic Rocks, secondary, from I and II.

CHAPTER XI

SEDIMENTARY ROCKS

The Composition and Character of Sedimentary Deposits

Sedimentation and Stratification. — If material of various degrees of fineness be dropped into still water, the heaviest and coarsest particles will descend and reach the bottom first. Upon them will fall the next in size, and so on to the top of the deposit, which will consist of the finest ones, thus making a regular gradation from bottom to top. If the water, instead of being still, were moving in a regular current, the gradation would not take place wholly in a vertical direction, but in a horizontal one as well, the successively finer material being dropped farther and farther along the bottom. This material would be graded, but not stratified. If, however, the process be repeated, and the velocity of the current changed even to a slight extent, since in a foregoing part of this work (page **42**) it has been shown how greatly the size of particles, which can be carried by moving water, depends on the velocity of the current, it will happen that, although the new deposit will be graded as before, at no point will its degree of fineness exactly correspond with that of the previous layer vertically under it. The two layers will be separated by a distinct juncture plane, on either side of which they will differ in texture; this is *stratification*, and the juncture plane is called a *bedding plane*. It is clear that to obtain stratification there must be varying size of particles and velocity of current. Now as all currents, whether streams on the land or tidal ones in the sea, are constantly varying from place to place and from time to time, the deposits of the sediment, which they may carry and drop as they slacken, are always distinctly stratified, that is, made up of parallel layers, or beds, which may differ in thickness, texture, and materials. A given layer may be part of an inch, or a hundred feet or more, in thickness, and it represents a period during which the conditions of deposition were uniform. A great thickness of very fine material indicates a prolonged interval of quite regular conditions, and the probability of the deposit having taken place on the sea-floor, or in some large lake. A single layer is known as a *bed,* or *stratum,* and a close examination may show that this is made up of

much finer layers, which may, indeed, be as thin as paper, and are known as *laminæ*. See Fig. 204. A collection of beds, lying concordantly above one another, deposited during a minor geological division of time, and with similar characters, is called a *formation*.

Matter carried and deposited by air currents may also be stratified, though generally much more rudely than when the work is done by water. Thus in a volcanic outburst the ashes driven by the wind may spread over a wide extent of country; the heavier and coarser particles fall first, to be succeeded by

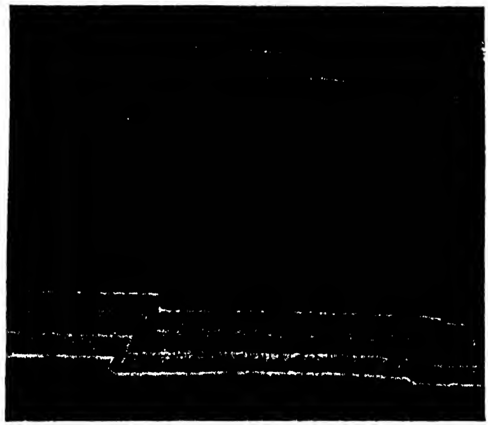


Fig. 204. — Thin laminæ composing part of a bed of sandstone, natural size. The displacement, or fault, has occurred since deposition.

finer, and, finally, by dust. This produces gradation, but, if a new outburst occurs, the coarser particles first falling will rest on the finer of the previous eruption, and a continuation of this process will give rise to stratified beds of volcanic tuff, as may be seen in many parts of the Rocky Mountains. On the other hand, deposits of loess (page 18) show little or no stratification, indicating general uniformity in the size of the particles, and conditions of deposition.

But, while deposits made by the wind, such as drifted sand or volcanic ashes, are sometimes rudely stratified, these are of small importance compared with the great masses of material which are, and have been in times past, carried and laid down by moving waters, and, as shown above, such exhibit by their stratification the manner in which they have been formed. See Fig. 205.

Materials Involved. — The material which currents are able to transport and deposit, whether upon the land or in the sea, may have one of two modes of origin. It may be either the waste of the land, or matter produced by life in the sea. The first may be considered mechanical, the second organic in mode of formation. The waste of the land, through the destruction of previously existent rocks by various erosive processes, and its transport have been

already treated in the foregoing part of this work, as has also the production of lime carbonate deposits by living organisms in the sea. They need, therefore, only this mention to show the contrast between them, one kind of material being of continental, the other of marine origin. There are other kinds of deposited material, such as rock salt, but these are of such minor importance that they need not be considered, at present, in this connection.

Fig. 205. — Regularly bedded sandstones and shales, near Pueblo, Colo. G. K. Gilbert, U. S. Geol. Surv.

The land waste, according to the size of the pieces, or particles, is roughly graded into *gravel, sand* and *mud,* or *clay,* as follows:

Gravel. — This is composed of material from the size of a pea up, and the individual pieces are termed *pebbles;* large loose fragments of rock are called *bowlders.* Pebbles which have suffered a long transport in the beds of streams, or have been much rolled by waves on the shores of seas and lakes, have a characteristic rounded appearance. This depends also on the hardness of the substance composing them. The mineral quartz, on account of its hardness and durability, is one of the commonest substances forming pebbles, but other kinds of minerals and rocks, such as granite, basalt, limestone, etc., are frequent. Sediments are sometimes composed of pebble-sized fragments which still retain their rough, angular shapes; in this case we judge that they have suffered little movement and are not far from their place of origin.

Sand. — Material composed of particles smaller than peas, and

yet sufficiently coarse so that it will not form a mass cohering when wet, is known as sand. An ordinary sand would be like granulated sugar in fineness. It may be seen with a lens that the grains of coarser sand, such as is found on sea-beaches, are rounded like pebbles by attrition, but in the finest sands they may be angular. Quartz so commonly forms sand that, unless otherwise stated, quartz-sand is understood. Many other minerals are found in sands, and on the beaches of coral islands the grains may be made wholly of lime carbonate.

Mud, Silt, Clay. — This is the finest part of the land waste and when dry it may form dust. It coheres when wet. As a sedimentary deposit it is found off-shore, or in sheltered parts of estuaries, gulfs and bays where the slow movement of the water does not permit the transport of the heavier sand and gravel, or on the flood plains and deltas of rivers. As quartz is the characteristic mineral of sands, so is kaolin that of many muds and especially clays; as shown under the formation of soil, it is made by the decay of the feldspars of the rocks. In the destruction of the latter, since the quartz particles are heavier, while those of clay are extremely light and fine, there tends to take place a separation of the two by moving water; the quartz grains deposit first, forming sand, while the light clays settle later, or are carried beyond into still water.

In summation, then, it is seen that the sedimentary deposits consist mainly of *sand, clays* and *carbonate of lime,* and their varied intermixtures; gravels are of less importance in quantity, though geologically of great interest, as we shall see later. Carbonate of lime deposits have been already treated in the chapter on the work of organic life. Volcanic ash, organic matters such as peat, common salt, and gypsum are also deposited materials, but, although of interest and of local importance, they are not of the same geological consequence as those mentioned above. For glacial deposits see page 144.

Places of Deposit

The places where moving waters may deposit sediment can be divided into three: the land, the beach or area between the limits of average high and low tide, and the sea-floor. They may thus be classified as *continental, littoral,* and *marine* deposits. Since the distinction between these is a matter of great geological importance they must be considered separately, in some detail.

Continental Deposits. — The formations made upon the land by

moving waters may be divided, according to their origin, into the following classes:

Desert Deposits of Arid Regions.
Piedmont River Deposits.
Basin Deposits of Humid Regions.
Sub-aërial Delta Deposits.

Each of these is of sufficient consequence to demand some consideration, as follows:

Desert Deposits. — It has been previously shown, page 82 and following, that in all the continents interior drainages exist, caused by the excess of evaporation over rainfall. In such regions the land waste of the slopes of the basin constantly tends to move toward the more central parts and to form deposits. It may be moved by rivers into permanent lakes, like Great Salt Lake and the Caspian Sea, slowly filling them up, or in times of rainfall temporary streams may spread out in thin sheet-floods over lower level areas, giving rise to temporary lakes (playas), in whose waters the sediments brought down may settle. Thus, through the continued action of rain-wash and streams, aided by wind drift in times of dryness, the desert basins tend to fill up by deposits, which may become very thick, though at times and in places a reverse action through the export of material by the wind may thin them. Such deposits often contain layers of salt and gypsum as characteristic features, for reasons explained under salt lakes, and are apt to have a red coloration, as explained on page 172. See also work of the wind, page 13.

Piedmont River Deposits. — Where a young and lofty mountain range is undergoing extensive erosion, it may happen that the rivers draining it become so heavily loaded with sediment, that, when they issue upon the piedmont belt (piedmont, foot of mountain) of country below, their slackening current is unable to carry it all, and the part of the burden in excess of transporting power is deposited. In this portion of its course a river may, therefore, be aggrading, instead of eroding, and in times of flood its deposits may be widely spread over the adjacent country. Through the continued action of this process, during a long period of time, extensive deposits of sands and clays of great thickness may be formed. This is illustrated by formations lying upon the Great Plains and other areas of country at the foot of the ranges of the Rocky Mountains' tract in western North America, in similar ones in South America upon the Pampas east of the Andes, and upon the piedmont plain of India at the foot of the Himalayas.

It used to be considered that these deposits (of the so-called Tertiary period) in western North America, whose fossils indicate them to be of fresh-water origin, had been laid down in extensive lakes then existing, but more extended study has shown that, while in part this view may be true, it is not a necessary one to explain them, since, as indicated above, they may be equally well formed by aggrading rivers, and that they have been made for the greater part, if not entirely, in this manner. Ultimately, if not saved by some intervening geological process, as subsidence and covering by new sediments, such deposits in their turn must be eroded and carried away into the sea, the final depot of land waste.

Basin Deposits of Humid Regions. — In several of the continents basin-like depressions occur of variable extent and depth. Where the climate is arid, and the rainfall consequently small, these may give rise to interior drainages, as previously described. But, if the rainfall of the region is considerable and in excess of evaporation, as discussed under lakes, these depressions, if deep, may give rise to lakes, such as the Great Lakes of North America, or, if very shallow, to wide swampy regions covered more or less completely at times with shallow water, like the basin of the upper Amazon and its tributaries. Such lake basins must obtain important deposits from inflowing streams, and may eventually be filled up, while the shallow swampy areas receive muds and clays from the outstanding waters of flooded rivers, and these are mingled more or less with organic matter from the decay of the vegetation which flourishes abundantly in such places. This swampy condition, with resulting accumulation of river sediment, may be indefinitely maintained if the basin is a region of continued subsidence. Though deposited in water, such sediments are to be regarded as continental in origin, since they occur in hollows of the land surfaces. Not only are such deposits forming now, but they have been made extensively in times past, as we shall see later.

Delta Deposits. — The deltas of rivers represent so much land reclaimed from the sea, or from a lake. The structure of the deposits is similar in both cases, except that, in the lake, they are influenced by feebler waves and currents. Lake deposits have been considered in the foregoing section; what follows relates chiefly to deltas formed in the sea. The process begins by the deposition of sediments on the sea-floor; gradually these are built up on the front of the advancing delta until water-level is reached, and they then become land. The low-lying land is flooded in times of high water and more material laid down, and this continues until, in a vertical direction, a balance is reached between upbuilding in periods of highest flood and erosion at other times. Meanwhile, in a horizontal

direction, the delta is advancing seaward. Thus we see that a delta consists of a mingling of marine, littoral, and continental deposits, and this is because it is situated in the debatable zone where land and sea struggle for mastery. The structure of a delta is shown in Fig. 206. The finest material is carried farther out and forms beds

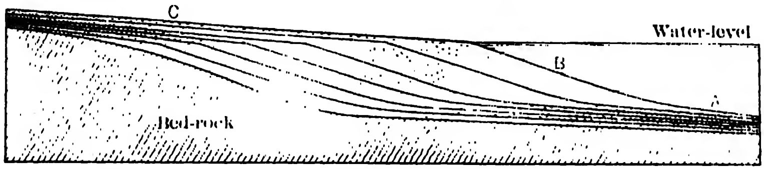


Fig. 206. — Illustrating section of delta built out in quiet water, of constant level. *A*, bottomset beds; *B*, foreset beds; *C*, topset beds. After Barrell.

horizontal, or nearly so, which are known as the *bottomset* beds. Down the slope of the advancing delta are dropped the coarser sediments, which make the inclined *foreset beds.* As stated above, deposition also happens on top of the delta, forming the *topset* beds, which are horizontal, or nearly so. Thus the foreset and bottomset beds are marine deposits, the topset beds may be largely land, or continental ones, while the littoral or beach zone is of minor importance. The deltas of great rivers, like those of the Mississippi and Nile, are built out in epicontinental seas on the submerged continental platforms, and, in such cases of wide extent, the difference

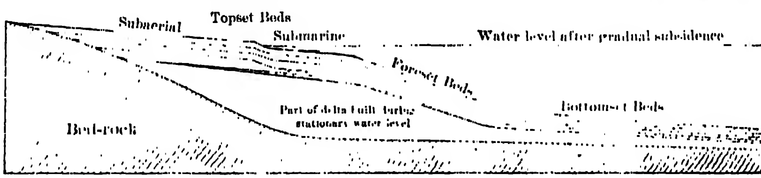


Fig. 207. — To illustrate conditions in a subsiding delta. A portion of the delta built during a period of stationary water-line shows below. Through subsidence the water-line has advanced to the left. The topset beds are partly subaerial and partly submarine in origin. The foreset and the bottomset beds are relatively thin; compare with Fig. 206. After Barrell.

of angle of slope, and the distinction between the foreset and bottomset beds, mostly disappears. It has often happened that such shallow seas in times past have been filled by delta deposits, which are, therefore, as we shall see later, of great geologic importance. It has already been mentioned in discussion of subsidences of the earth's crust, that the deltas of large rivers are commonly areas of subsidence, and this, as shown by the thickness of sediments exposed, has frequently happened in the past. When a delta is subsiding, in contrast to one which is stationary, the upbuilding in a vertical

direction increases at the expense of its horizontal extension; if the movement is pronounced the latter may be small.

In a *subsiding* delta the river currents tend to become more sluggish through decreasing grade, and the flooding of it more frequent. This results in a greater increase of material dropped upon the topset beds; the latter may thus become the chief contributors to the delta growth. If the area of the latter is great, it may thus happen that the volume of land deposits, formed by the topset beds, may be vastly greater than that of the foreset beds which build out the delta's front. This relation is shown in Fig. 207. Consequently a delta which is growing upward because of a subsiding foundation tends to form dominant topset beds of continental nature; a delta growing outward because of a stationary one tends to form a greater volume of subaqueous beds.

Littoral or Beach Deposits. — The beach is defined as the area lying between average high and low tides. If the slope of the land to the sea is sharp, it may be a very narrow zone, or in the case of sea-cliffs be wanting. If the inclination of the land is very gradual, it may be of wide extent, and consist chiefly of areas of salt marshes and tidal lagoons, exposing mud flats at low tide. Such are well shown in the shallow sounds of North Carolina back of the barrier beaches, and in the wide estuaries of Delaware and Chesapeake bays. See page 108. Over these areas sands and muds are laid down as deposits; but generally along the shore, where the waves are cutting into the land, and the beach or littoral zone is very narrow, and exposed to the rush of the waves and tidal currents, only the coarser materials such as gravel and sand are able to accumulate. Coarse sand and gravel, then, are the most characteristic features of beach deposits, and they cannot be of great thickness, for, if the land is building out into the sea, they must give place to land deposits and be buried under them, or, if the sea is encroaching on the land, they must yield to marine sediments and be covered by them. The importance of this will be seen when the geological structure known as a nonconformity is discussed later.

Marine Deposits. — The most active region for the deposit of land waste on the sea-floor is in the shallow water, extending from the average limit of low tide out to the depth of 100 fathoms and thus upon the continental shelves, and also in the basins of epeiric seas (page 111). Over these areas the deposits are largely *terrigenous* (of land origin), consisting chiefly of sands and muds brought into them by rivers, or formed by the waves gnawing on the coasts. The finer, lighter muds tend to extend farther out into deeper water, and may be met 200 miles from land extending down the slopes of the ocean basins. These marine deposits have already

been described under the work of the ocean, page 111 and following, and need no further mention.

Enormous deposits, chiefly of carbonate of lime, have also accumulated on the sea-floor in times past through the agency of living organisms, and are forming at the present time. The character of these deposits, and the conditions necessary to produce them, have been stated under the geological work of organic life, page 190 and following. It need be only remarked that the occurrence of such deposits is, in general, indicative that the seas in which they were laid down were of clear water and possessed moderate to warm temperatures.

Consolidation of Sediments. — The stratified rocks are commonly in a very different condition from that in which they were laid down as sediments. Were it not, indeed, proved by the strati-

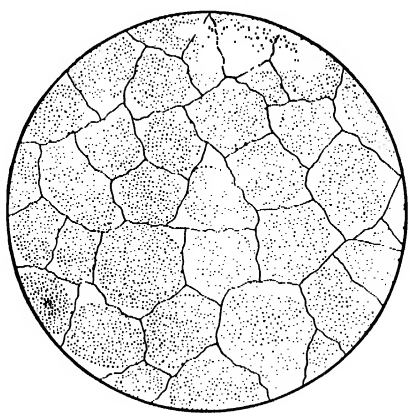


Fig. 208. — Section of sandstone (quartzite) under the microscope. The dotted areas are the rounded sand grains; the clear ones the silica deposited about the grains, binding them into rock.

fication, the contained fossils, and other features, it would be difficult in many cases to recognize their origin; to perceive in hard dense rocks what were originally soft clays and sands. The causes of consolidation are many, and often complex. For one thing, there is the long-continued and heavy *pressure*, exerted by masses which may be many thousand feet in thickness. Another important factor is the deposition of material from solution in the spaces between the grains, which *cements* them together. There is, in greater or less degree, a constant leaching of material from the upper layers by percolating waters, and a transfer and deposition of it at lower levels. The most common cementing substances thus deposited in the

rock-pores are carbonate of lime, silica, and oxide of iron. The interstices may become almost entirely filled with cement, as illustrated in Fig. 208, and the sediments thus converted into very firm solid rock.

The interior heat of the earth rising into such masses of sediments may aid in some degree to consolidate them by quickening the chemical and mechanical activity of the diffused waters which deposit the cement. And, finally, since the conversion of sediments into rock must be a slow process, *time* is an important element in the case. Thus we observe that, in general, where the more recent sediments have been converted into land surfaces, they exhibit much softer and more friable stratified rocks than the older ones. It must not be understood, however, that this process of cementation takes place only under the sea, for on land also the same process of solution, transfer to lower levels, and redeposition can be going on.

Kinds of Sedimentary Rocks

The different kinds of sedimentary rocks depend upon the nature of the sediments from which they are formed, and the degree of consolidation, or compactness, which they have assumed. Thus, calcareous muds on drying may form a *chalk*, through pressure and cementation they become *limestone*, while the latter through certain agencies to be described in a later chapter and known as *metamorphism* may become densely hard and crystalline, and is then called *marble*. The discussion of the stratified rocks which have been subjected to metamorphism is, however, deferred to that chapter in which this subject is treated; here only those cases are considered where the sediments have been consolidated by pressure and cementation, as previously described. The chief sediments and the rocks they yield are, then, as follows:

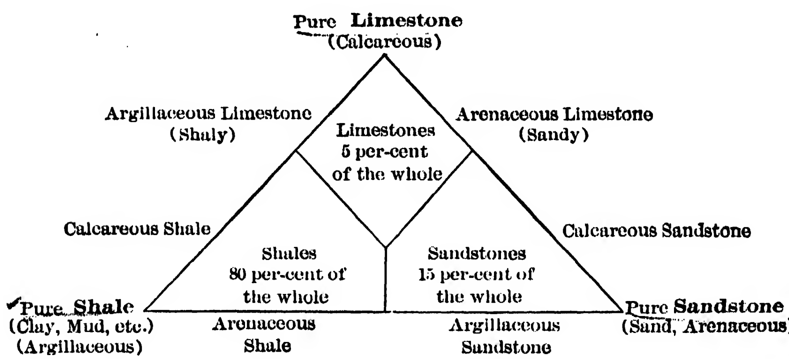
Sediments	Compacted strata, as rocks
Gravel	Conglomerate
Sand	Sandstone
Silt and clay (mud)	Shale
Lime deposits	Limestone

Gradations of Rocks. — It must not be imagined that the different kinds of rocks mentioned above are always sharply defined from

one another as clear distinct types. This is very far from being the case. Just as muds grade through sand into gravel, and pure lime deposits into muddy ones, so may the various rocks formed from them grade into one another.

At this point it may be well to explain the usage of certain terms frequently employed in connection with sediments and stratified rocks. Of the finer deposits, or muds, clay is the most important representative; the word clay is of Anglo-Saxon origin, its adjective is *clayey,* the corresponding word derived from the Latin is *argillaceous* (from the Greek argillos, clay). Similarly the adjective *sandy* has its Latin equivalent in *arenaceous* (from arena, sand — the place where gladiatorial combats took place was so called because covered with it). The adjective limy, little used, has its counterpart in *calcareous* (from the Latin calx, lime, limestone). These adjectives, argillaceous, arenaceous, and calcareous, are constantly used with reference to the sediments to which they belong and the rocks composed of them.

The gradations of the various kinds of stratified rocks into one another may be illustrated in the following diagram:



We are, therefore, accustomed to speak of calcareous sandstones, shaly limestones, etc., as indicated in the above diagram. The percentages in it give the relative estimated proportions, in each kind, of the total volume of all sedimentary rock; thus shales are sixteen times as abundant as limestones.

The characteristic features of those stratified rocks which are of greatest importance are the following:

Conglomerate. — The rock consists of pebbles or fragments held together by a base or cement of some kind. The pebbles, which compose the gravels from which these rocks are formed, are generally rounded. Quartz is the most common substance constituting them, but they may consist of pieces of definite rock, such as granite,

basalt, etc. Such pebbles may vary greatly in size, from a fraction of an inch to a couple of feet, or more, in diameter. The appearance of a conglomerate is shown in Fig. 209. When the contrast of pebbles and cement is clearly marked, such rocks are sometimes called *pudding-stone*. When the rock is composed of angular fragments, which is sometimes the case where the material has suffered

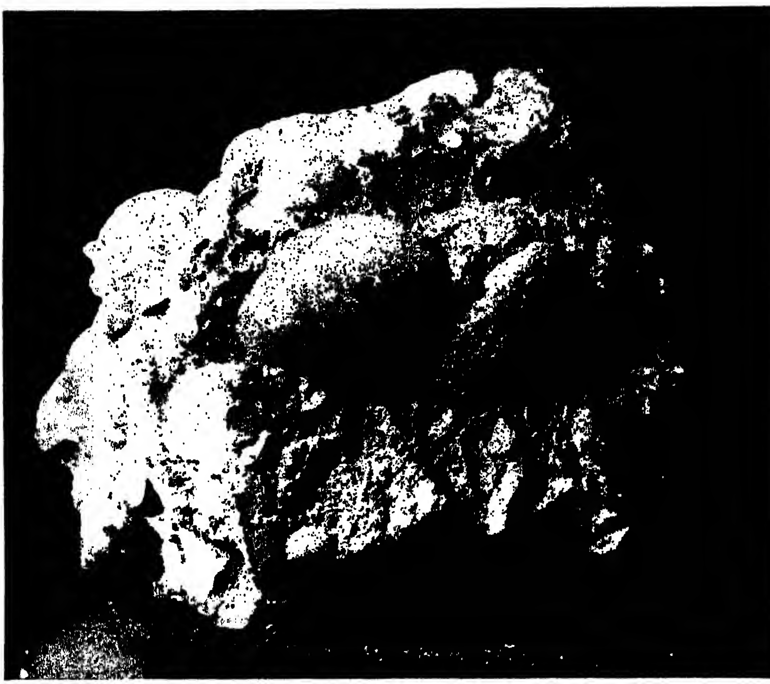


Fig. 209. — Conglomerate; the pebbles in this case are about the size of an egg, and composed of several different kinds of rocks.

no transport, or only a short one, it is called *breccia*. Some conglomerates show by their characters, especially by the grooved and striated surfaces of the pebbles and the facets ground upon them, that they are ancient bowlder-clays, or tills, the morainal deposits of glaciers and ice-caps of past geologic ages. See page 144.

Sandstones. — These are usually quite even in grain and vary from friable to firm, according to the strength of the cement. The grains are composed wholly, or mostly, of quartz. In the red and brown varieties the cement is mainly oxide of iron; in the white, buff, gray, or pale brown, carbonate of lime; the question of their

solubility has been already discussed, page 162. Sandstones are generally very porous rocks; 30 per cent of their volume may, indeed, consist of interspaces between the grains; they are, therefore, favorable strata in which to find artesian water. See page 158.

Arkose is a variety of sandstone which contains much unaltered feldspar. Its occurrence indicates that the component material has not been long exposed to weathering, and has, therefore, probably not been transported great distances. It is thus more likely to be of continental, than of marine, origin, and to be produced by the breaking down of rock in lands with cold, arid climates, rather than in those with warm humid ones where rock decay is rapid.

Graywacke. — This is a sandstone-like rock of prevailing gray color, composed of grains of various minerals and tiny fragments of other rocks. It is really a very fine-grained conglomerate, or not infrequently passes into one by increase in the size of the particles. It may also be of continental origin.

Shale. — This name is given to compacted muds and clays which possess a more or less thinly laminated, or fissile, structure, along which they may be rather easily cleaved. This parting is parallel to the bedding and is the result of natural stratification. Where shale beds have been subjected to folding and pressure, by crumpling of the crust, they become generally harder and assume a slaty cleavage which is distinct from stratification; the rocks are then slates, not shales, and will be discussed under metamorphic kinds in a following chapter. Shales are soft rocks, can be cut with a knife, and are apt to be brittle, and to readily break up into small chips. They show a great variety of colors from light to dark; in the latter case organic matter is present. Like clay, of which to a greater or lesser degree they are composed, they yield a characteristic odor when breathed upon. Unlike sandstone, they tend to be impermeable to water.

Limestones. — The chief varieties of the carbonate rocks are *limestone proper* (essentially carbonate of lime, $CaCO_3$); *dolomite*, in which more or less of the lime has been replaced by magnesia to form the dolomite molecule $(MgCa)CO_3$, and chalk. These, and some of their sub-varieties, such as coquina, have been described under organic life, page 190 and following, where their origin is treated. Limestones are usually bluish in color, or vary from pale gray to black, dependent on the amount of organic matter they contain; sometimes they are yellowish or brown. They are generally very dense, compact rocks, in some cases very homogeneous, in others more or less filled with shells, or other fossil forms. They can usually be distinguished from other rocks, which they may

resemble, by the readiness with which they can be scratched, or cut, and by their effervescing when treated with acid.

Some Minor Sedimentary Rocks.— In this connection brief mention may be properly made in this place of some minor varieties of sedimentary rocks. They are *coal, iron-ore, rock-salt,* and *gypsum.* The reason that they are spoken of as minor deposits is, that, although of vast importance from the human standpoint, geologically they occur in volumes so limited, as compared with the enormous bulk of the shales, sandstones, and limestones, as to be of little importance, when considered merely as rock masses.

a. Coal.— The formation of peat and its relation to coal has been already mentioned, pages 175–180. When peat changes into coal the process is a gradual one; the organic material is buried in layers of clays and sands, and as these change into shales and sandstones, it is turned into coal, by loss of volatile matter and pressure. This takes place in various stages; first, brown coal or *lignite* is formed, a rather soft, lusterless brownish material with about 60 per cent of carbon; in a more advanced stage this becomes *soft* or *bituminous* coal, a compact, black, brittle rock with 75–90 per cent carbon; under proper geologic conditions, soft coal may change to *anthracite,* a dense, black, shining rock, with 80–95 per cent of carbon. Further details regarding the nature of this change, and the formation of coal, will be found in the second part of this work in connection with the occurrence of coal.

b. Iron-ore.— Beds of iron-ore varying from a few inches to many feet in thickness, are often found in association with stratified rocks, and in varying degrees of purity. It is either limonite, the hydrated oxide of iron, or siderite, ferrous carbonate One mode of formation has already been treated of, pages 172 and 181. Other information respecting these ores will be found on page 421, as minerals in the Appendix, and concerning their occurrence in the second part of the book.

c. Rock-salt.— Beds of salt are also found associated with stratified rocks, especially with clays and shales; they are rather limited in area, but sometimes of enormous thickness. The manner of salt formation has been considered on pages 84–89.

d. Gypsum.— This substance, the hydrated sulphate of lime, is produced under arid conditions, like salt, which indeed it is very apt to accompany, though it also occurs independently. It is found mostly in thick lenses, or beds of limited area. Its mineral characters are stated in the Appendix, and occurrences are given in Part II.

Characteristic Features of Sedimentary Rocks

In addition to the ordinary stratification, which these rocks exhibit as a proof of their mode of origin, they also possess other features, some of them minor ones, it is true, but none the less of significance, which enable us to determine the places where the sediments were deposited and the conditions under which the deposition took place, and to thus throw light upon the geological history which they record. Some of the more important of these features may be tabulated as follows:

Fossil Remains of Former Life.	*Ripple- and Rill-marks.*
Foot-prints.	*Cross-bedding.*
Rain-drop Impressions.	*Conglomerate Structure.*
Mud-cracks.	*Oolitic Structure.*

Tracks of Animals.

Fossils. — It is a common and well-known fact that the stratified rocks contain in variable amount the remains of animals and plants inhabiting the earth in former times. Sometimes these consist simply of the *impressions* of the organisms in the rock, sometimes in the actual *preservation* of their *hard parts,* such as bones and shells, and sometimes in the complete *preserval* of the whole *organic structure* by its entire change into stone (petrifaction), particle by particle, as the organic matter decayed, or was removed. Great diversity in the fossils of the rocks is found in several ways, and for obvious reasons. Thus they may vary according to the kind of rock, or, as it is said, change according to the rock facies; the kinds of animals that live in muds differ from those inhabiting sands, to a certain extent, and thus sandstones are liable to contain different fossils from shales. Fishes, which are free-swimming animals inhabiting both salt and fresh water, might furnish fossils in nearly all the different kinds of deposits, either continental or marine, while the bones of land animals would be expected in the former rather than in the latter, especially in sandstones. Also the fossils found in the earlier rocks are very different kinds from those of the strata formed in later geological periods, and we learn by attentive study of this fact that there has been a constant evolution of life upon the earth, from very simple to more and more complex types of organic structures. And, finally, just as we know that the associated animals and plants of one part of the earth (its fauna and flora) differ from those of another part, so do the fossils of one region differ from those of another region. The further back in the rocks we go, however, the less marked do we find this difference, since the nearer do we approach to the less modified and simpler types of marine life.

All these are facts of the highest importance, and the manner in which they are used in deciphering the past history of the earth and its inhabitants will be set forth in detail in the second part of this book.

Foot-prints, and Rain-drop Impressions. — These are features not infrequently found in stratified rocks, and the conditions under which they are formed appear to be as follows: The tracks of large

vertebrate animals made in soft muds and clays of the land surfaces of to-day, as in the time of spring rains and floods, become, later in the season, especially in arid and semi-arid countries, baked to an almost brick-like hardness, and may endure for several years before they are effaced. The same is true, in lesser degree, of the tracks of birds and small mammals, and the pits made by the rain-drops of a passing shower. This could hardly occur where the deposit was kept soft and frequently washed, as in humid regions, with much rainfall, or on mud-flats constantly subjected to the action of the tide. But, on the mud-flats of river plains and deltas, and on the shores of interior basins of arid or semi-arid regions, we can imagine such impressions formed, hardened, and then covered by deposits blown by the wind, or swept by the waters of the next flood-time, and thus preserved. They are thus essentially features of continental deposits, and will only rarely occur in those of the littoral regions of the sea, where, possibly in the mud-flats at the heads of estuaries, conditions favorable for their production, such as unusually high tides, might sometimes be present. Since impressions in sand generally do not retain their shape or are quickly effaced, it is evident that these prints must be usually made in mud, or muddy sands, to be permanent, and this means that those of former ages will be found chiefly in *shale*, or very shaly sandstones, as this is the rock-form of compacted muds and clays. Examples of foot-print and rain-drop impressions in shale may be seen in the second part of this book. It is of course clear that such impressions could not be found in true marine deposits.

Mud-cracks. — What has been stated above of foot-prints is quite as true of mud-cracks. Soft muds left exposed by the recession of high water dry and crack into polygonal forms, as illustrated in Fig. 210. Further exposure to the sun bakes and hardens the blocks. During the dry season these are often covered and preserved by wind-blown silt or sand. In other instances, at the next period of high water, these cracks will be filled with the coarser sediment first deposited, and the whole record buried and preserved by succeeding deposits. After the whole series of deposits has been hardened into rock, usually with subsidence beneath the sea and subsequent emergence, the layers of shale, which the muds and clays form, may be exposed by erosion, quarrying, etc., and will then exhibit these mud-cracks. It may happen that in taking up the rock-layers the soft shale beds will break away, leaving the filling of the mud-cracks projecting from the lower surface of the overlying layer, thus furnishing a natural cast of the cracks. As

in the case of foot-prints, it is obvious that the most favorable places for their occurrence will be on the flood plains of rivers, on the wide flat shores of shallow interior lakes, and less prominently at the upper margins of shallow estuaries of the sea, and especially under arid or semi-arid conditions of climate, where time for sun-baking and hardening occurs between periods of flood-water. They are thus characteristic features of continental deposits, minor and restricted ones of littoral deposits, and in marine deposits will be generally wanting.

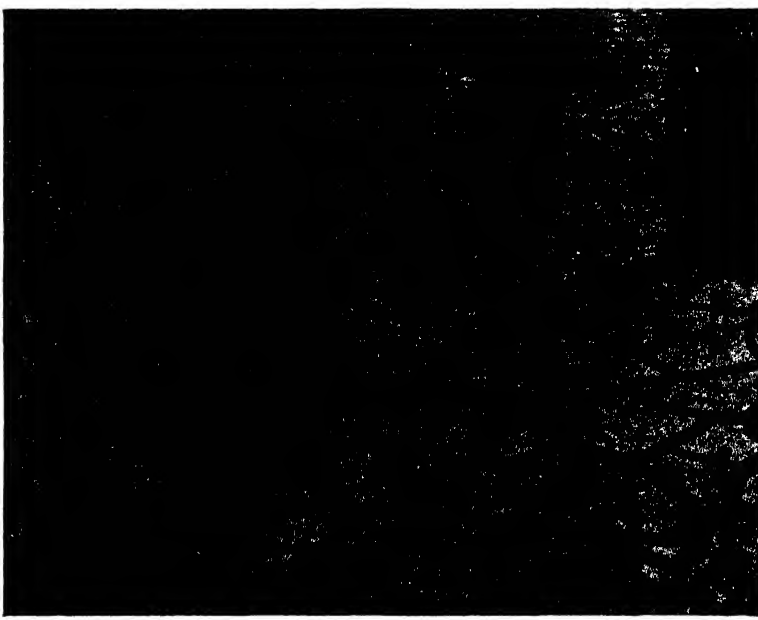


Fig. 210. — Mud-cracks, delta of the Colorado River. G. K. Gilbert, U. S. Geol. Surv.

Under certain conditions, however, which have sometimes occurred in the geologic past, the recession of stretches of very shallow sea-waters, through other causes than the tides or infilling by sediments, has resulted in the drying and cracking of marine sediments, especially of limy oozes, but it is to be noted that the structure still signifies a continental origin. Thus mud-cracked limestones are not infrequently observed.

Submarine Tracks. — Other markings and structures are observed in the stratified rocks, which by study and comparison with similar features found in modern sediments, are referred to the tracks made by marine animals, such as crabs walking on the bottom, to the trails left by worms crawling, and to the filling of burrows dug by such animals in the deposit. They can occur only when the material has a tenacity adequate to retain the impressions until

covered by the next sedimentation; it must, therefore, be neither too soft nor too crumbly. Sand mixed with considerable clay, giving rise to shaly sandstone, is the most natural medium. Such impressions on a beach, subjected to the ebb and flow of the tide and the action of waves, could, in general, not be permanent; hence their occurrence is indicative of marine deposits, formed especially in shallow water.

Ripple-marks. — If one observes a sandy bottom in shallow water, it will be frequently noticed that the sand has been thrown up

Fig. 211. — Ripple-marked sandstone.

into a series of small parallel ridges by the action of the waves. These are known as *ripple-marks.* While they may also be formed in sand on land by the action of the wind, as on sand-dunes, see Fig. 5, they are also characteristic of wave action in shallow water. They are not directly heaped by the waves, but are caused by the oscillatory motion which these give to the water, and, while generally formed in depths of less than 100 feet, they may, it is stated, corrugate the bottom in very fine sands up to 600 feet after heavy storms. Such furrowings may be preserved by later deposits, and, when consolidated into stone, give the rock surfaces a characteristic appearance when split or exposed to erosion, see Fig. 211.

In deep water the ripple-marks appear to be symmetrical, closely spaced, and due to wave action. They have been termed *oscillation-ripples.* In shallower water they may be caused by currents, and are not symmetrical; the

gentle slope is on the side of current arrival; these are *current-ripples.* In shallow water there may also be produced *giant-ripples,* due to tidal action, with crests possibly 6–8 feet high and 60–100 feet apart; see also remarks on heaping by stream traction, page 42.

Ripple-marks, in their size and spacing, depend in some measure on the coarseness of the grains, and on the depth, being more closely spaced with fine material and in deeper water, and to a less degree on the intensity of winds and waves.

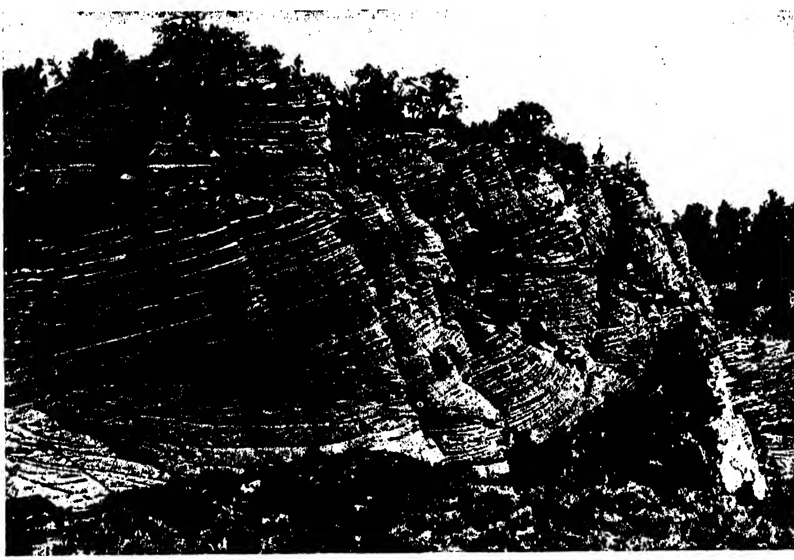


Fig. 212. — Cross-bedding in sandstones. The large scale on which it occurs indicates a probable æolian (dune) origin. Walnut Canyon, Ariz. J. K. Hillers, U. S. Geol. Surv.

Wave-marks, occasionally seen on the surface of strata, are the curved lines of material washed up on the beach at the inshore edges of waves, while *rill-marks* represent the little diverging channels cut by the returning under-tow in passing over pebbles and other obstacles in the sand, or by rain water running over exposed flats. These are indicative of littoral and continental deposits, although it is possible that somewhat similar markings may also be æolian in origin.

Cross-bedding, or Oblique Lamination. — It is frequently observed in strata composed of the coarser detritus, such as conglomerates and sandstones, that the laminæ of particular beds, instead of being parallel to the general planes of stratification of the series, are inclined to them, often at considerable angles, and perhaps curved as well, as shown in the illustration, Fig. 212. This structure is known

as *cross-bedding*, or *oblique* lamination. It usually indicates rapid deposit in shoal water by quick and shifting currents, and is liable to occur in the foreset beds (page 277) of deltas, bars, spits and barrier beaches, where the material is dropped down the forward slope of an advancing deposit. It may happen in rivers, lakes and the shallow waters of the sea, and thus be found in continental, littoral, and marine deposits. It is also the characteristic structure of wind-built sand-dunes where the material is rapidly shifted about and

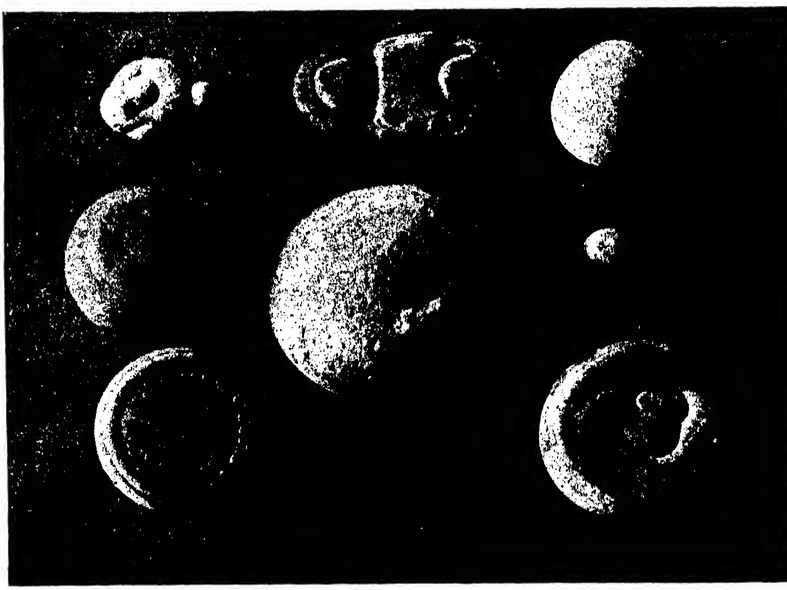


Fig. 213. — Concretions from clay beds, Long Island.

commonly deposited on inclined surfaces. It may thus be æolian in origin and, therefore, again found in continental deposits. The cross-bedding of certain sandstones of the Colorado region, and of the chalky limestones of Bermuda has been considered to have this æolian origin.

Concretions, and Concretionary Structure

Concretions. — Stratified rocks in many places contain numerous inclusions of a nature different from that of the material enclosing them. These inclusions are apt to be rounded, and nodular in form; some occurrences are quite spherical, others flattened, ovate, elongated, ring-shaped, or compound and exhibiting odd and fantastic shapes. They may be a fraction of an inch in diameter or

many feet. The shapes of some are shown in Fig. 213 and the mode of occurrence in Fig. 214. They are often arranged in parallel layers. On breaking them open it is often found that the globular mass consists of matter aggregated about some object as a nucleus. Masses of this kind are known as *concretions*. In composition they are different from that of the main rock mass in which they lie, and are formed from one of its minor constituents; thus in chalk and

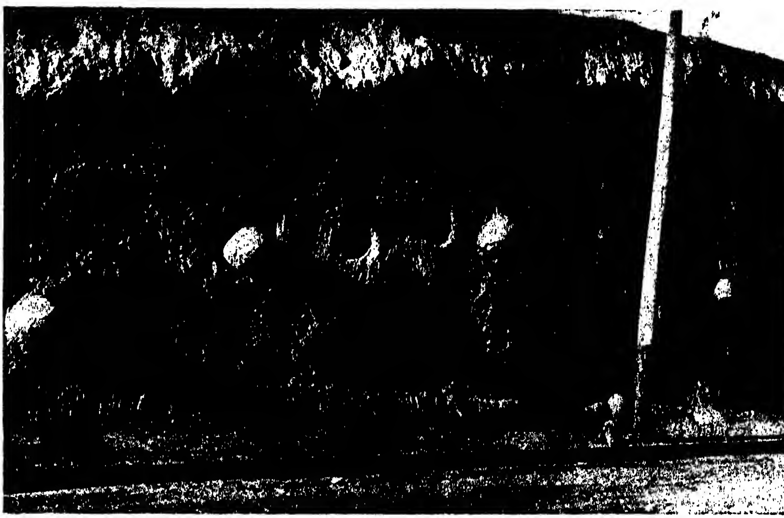


Fig. 214. — Concretions in clay, Los Angeles, Cal. R. Arnold, U. S. Geol. Surv.

limestone they are composed of silica; in sandstone, of iron oxide or carbonate of lime; in shale, of carbonate of lime or sulphide of iron. While some are very pure, they often contain large amounts of the rock-material, and in some cases the planes of stratification can be seen passing through them. Their origin appears to be due to material in the rock having gone into solution, and then for some reason having been steadily redeposited around certain centers as nuclei, thus building up the concretions.

Sometimes the bodies of animals or leaves of plants decaying in the sand or mud appear to have been the determinant cause of the formation of concretions, and to have served as the nuclei about which they collected. On splitting open such concretions, remarkable fossil imprints of ferns, insects, and marine animals like shrimps, fishes, etc., may be obtained. Or sometimes, when they attain huge dimensions, the shells and bones of large animals may be found enclosed in them. In other cases some inorganic substance, such as a grain of sand, may have formed the nucleus, while in others no definite nucleus can be found. In some concretions cracks occur in which mineral matter of another

kind has been deposited, seaming the surface with a polygonal network of veins; these are known as *septaria.* Iron-oxide concretions are not infrequently hollow, and more or less filled with sand. See also Fig. 18.

Flint and Chert. — Flint is a dark gray to black, very hard and compact substance occurring in irregular nodules, or concretions, in chalk. It is composed of silica, SiO_2, with a little chemically combined water. An impure flint, occurring in a similar way in limestones, is known as *chert;* it is sometimes seen in parallel layers and lenses in the rock. The silica composing these substances appears in some cases to have been derived from the hard parts of certain organisms living in the sea-water, such as sponges, radiolarians,

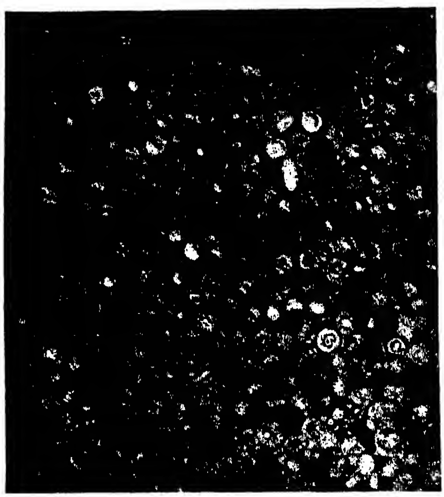


Fig. 215. — Pisolite, showing concretionary structure. Natural size. Bohemia.

teeth of worms, etc., which have gone into solution and been redeposited. Flint is a substance of considerable interest because, on account of its hardness, homogeneity, and lack of cleavage, it has been used extensively from prehistoric times down to the present by primitive peoples in the manufacture of implements and weapons, and for its employment in striking fire. Until a comparatively recent time, when percussion caps were invented, great battles and the fate of nations were decided by flint-lock guns. It has been observed that, in the weathering and decay of certain Paleozoic limestone formations in the Southern States, nodules and plates of flint are formed, which may accumulate thickly on the surface. The chemistry of this process is not well understood. Further details with respect to flint will be found in the Appendix.

In some places considerable masses of flint-like rocks occur on a scale which appears much too great for them to be explained by the origin mentioned above. The varieties are sometimes called *jaspilite* (Lake Superior region), sometimes *novaculite* (Arkansas), and sometimes other names are given to them. In some instances they are believed to have been formed from silica chemically precipitated from solution; in others their origin is uncertain.

Concretionary Structure, Oolite. — Concretions may become so numerous in a rock stratum that its entire mass is composed of them, giving rise to concretionary structure. While this has been observed in sandstones and in iron-ore deposits, as in the Clinton ores of eastern North America, it is mostly seen in certain limestone rocks. The concretions are generally minute, like small shot, and the rock in appearance resembles fish-roe, and hence is called *oolite* (egg-stone). A variety with larger concretions (Fig. 215) is known as pisolite (pea-stone). The oolite structure is not rare; indeed it is much more common in limestones than is generally realized.

On the shores of Great Salt Lake at the present time the sand is observed to consist of minute spherical concretions, like fine bird-shot, of carbonate of lime deposited from the lake waters. Similar sands are forming about some coral islands; such sands if compacted and cemented would form oolite, and in some places this formation of the rock is now taking place, thus throwing light on its origin in the past.

Dimensions of Beds; Overlap; Relative Age

Area and Form of Beds. — It is theoretically conceivable that if all the lands were beneath the sea a world-wide stratum consisting of deposits by marine organisms might form, and on re-elevation of the lands be everywhere found upon them. No instance of this kind is known and the teachings of geological history, as shown later, inform us that it has not taken place. On the other hand, beds of mechanical sediments, such as sandstones and shales, imply land surfaces from which they are derived, and basins in which they are laid down; it is obvious that their areal extent must be limited by the borders of the basins, next to which they must thin out and disappear. In geometric form, then, a bed must be lens-like, lenticular, thicker near one border than on the other, and commonly extremely flattened; in ground plan it need not be circular, but is usually much elongated and irregular. As a general, but not invariable, rule it is found that the coarser the material composing a stratum is, the smaller the area which it covers; thus conglomerates may die out rapidly in a few miles, or even less, and coarse sandstones may have the same inconstancy, while on the other hand, beds of shale and limestone have been observed to cover thousands of square miles. Also, dependent upon the law of sedimentation, see page 271, it is found that beds are thickest and coarsest near the source of supply, and thin out and become finer in texture as one

recedes from it. Thus, coarse sandstones are observed to grade into finer, and these into shales. It is sometimes stated that beds of stratified rock, if not changed from their original position, are parallel and horizontal when elevated to form land-surfaces. From what has been mentioned above it is clear that this is not absolutely true; yet the scale on which the beds form unsymmetrical lenses is usually so large that, generally, in the exposures, even over long distances, they may appear to rigorously follow this rule. See Fig. 205.

That the strata are not always laid down horizontally may be readily seen where cross-bedding (previously mentioned) occurs, and especially in the fore-set beds of small deltas, bars, etc. The inclination of such beds may be as much as 10° to the horizontal. Since the great extended beds of sediment have a one-sided lenticular form with the thickest edge next to the land, as they are piled on one another, the planes of stratification must have a gentle inclination seaward. But the scale on which this occurs is often so great that, as mentioned above, we may not perceive it.

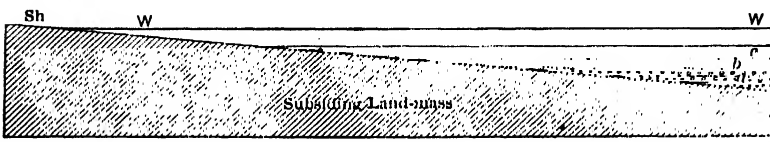


Fig. 216. — Diagram to illustrate overlap. On a sinking land, as the water, *WW*, continually moves inland on the shore, *Sh*, the successive beds of sediment *a*, *b*, *c*, are laid down more and more to the left, the edges of successive upper and newer beds overlapping those of the older and lower ones. On a rising land this relation would be reversed.

Overlap. — It is often observed in a series of strata that the edges of some beds extend for distances beyond those of beds below them, while the lower ones thin out and disappear. This relation is known as *overlap*, and the manner in which it originates may be understood by reference to the diagram, Fig. 216. This gradual advance of the sediments upon one another (or their retreat) is of interest, because it marks the position of ancient shore-lines, and indicates a sinking or rising of the land with shifting of the shore-lines, or, possibly, the sea itself may rise or sink. Overlap may also occur on a small scale in the filling by deposit of a basin with sloping sides. It must not be confused with nonconformity.

Thickness of Sediments. — It has been customary to ascribe great thickness to accumulated beds of sediments, or in other terms to stratified rocks, in certain places, especially in mountain ranges. It is very common to find them measured by thousands of feet; 5,000, 10,000 and 15,000 are not uncommon, and in some regions even greater thicknesses have been ascribed to them; the strata which now compose the Appalachian Mountains are held to be

30,000 feet thick in Pennsylvania, while those of the Alps have been placed at 50,000. It is obvious that if we accept such great thicknesses as correct, since the great bulk of the land-derived sediments is deposited near shore, it must follow that subsidence of the sea-floor also occurred to permit of their accumulation. For close to the shore we do not find water of any such depth — 30,000 feet, indeed, marking the deepest parts of the ocean. And even though these

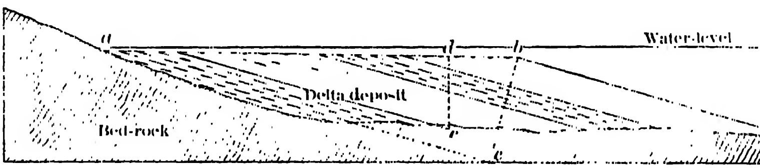


Fig. 217. — To illustrate apparent, as compared with real, thickness of strata. The figures show a delta deposit composed of inclined foreset beds. The real thickness of the formation is *ed*. The apparent thickness *eb*, obtained by multiplying the distance *ab*, the exposed edges of the uplifted formation, by the sine of the angle of inclination, *cab*, is evidently much too great. Modified from Chamberlin and Salisbury.

maximum thicknesses assumed may contain, as they usually do, marine deposits of carbonate of lime in large amount, in addition to the terrigenous material, subsidence would be just as necessary. But, while undoubtedly subsidence and the accumulation of sediments to great thicknesses, many thousands of feet, have occurred, it is at least questionable whether in the extreme cases, such as those mentioned, all the different data necessary for an accurate result in measuring the thickness have been taken into account. If the stratified rocks at the bottom of a series of strata, apparently accumulated to vast thicknesses, are of a character similar to those much higher up, or near the top of the series, it is improbable, for several reasons, that the whole was ever more than 15,000–20,000 feet thick.

An error may be made in estimating the maximum thickness of strata, in that the initial inclination to the horizontal and the overlap of the beds, mentioned above, have not been sufficiently regarded. This has been recently urged by Chamberlin and Salisbury, and the effect of it in causing error is illustrated in Fig. 217. On the other hand, this idea must be used with caution, for it assumes that in a thick formation the beds are chiefly *foreset* ones, deposited with a considerable angle of inclination, but, in a broad and thick formation made by a subsidence, the *topset* beds are the dominant ones, and these are deposited, as a rule, with exceedingly gentle angles of inclination. If the tilting of the upturned and eroded beds is steep, there is less error introduced by the customary method of estimating their thickness, while if they are only gently inclined, the idea involved in the figure may be taken into account.

Relative Age of Beds. — In a series of beds of horizontal strata piled upon one another, we assume that the higher a bed is in the set, the younger it is in point of age. This seems so obvious as to need no further demonstration, yet it is the basis of all our deciphering of geological history, and upon it, in fact, the science of evolutionary paleontology has been built. This substructure of geology is so humble and close to the ground, that it is often overlooked in the contemplation of the edifice which has been erected upon it; for the beginner, especially, it should not be lost sight of. If we should conclude, however, that the rule is invariable, in all places and under all conditions, that an upper stratum is younger than one appearing below it in horizontal position, we should fall into serious error, for there are some remarkable exceptions to it, as will be shown later on.

Deformation of Strata

Although over wide regions the stratified rocks appear to be lying, in a general way, in the horizontal position in which the beds were laid down, and to have been raised to form land surfaces, sometimes to great heights, without serious displacements, it is a matter of

Fig. 218. — Section 12 miles long showing folding in the Appalachian Mountains, near Greeneville, Tenn. Modified from Keith and Willis.

common observation that in other places, notably in mountain regions, this is not the case. Here, on the other hand, we find the strata inclined, often at high angles, thrown into folds, contorted, bent and often more or less broken. All such displacements may be included under the term of *deformation of strata*, which will now be described. The discussion of the most probable causes for this phenomenon will be deferred until later, when mountain ranges, in which it is so prominently displayed, are treated; only the structures themselves being here considered.

Folds: Anticline and Syncline. — Study of the strata, by methods to be presently mentioned, shows that in many places they have been corrugated into folds. Sometimes these are on a small scale and can be readily seen, Figs. 221 and 222; often the folding is on such a great scale that only here and there in cliffs, rock outcrops, etc., are portions of a fold exposed, which in the strata simply appear inclined, but by noting the inclination and following the outcrops of particularly distinguishable layers, sometimes for miles, the im-

mense size of the folds becomes clear to us. The manner in which strata have been folded, and the scale on which it occurs, may be seen by inspection of the adjoined section, Fig. 218, which has been worked out by geologists.

With respect to folding, two terms are constantly used by geologists. In a series of folds, it is evident that, like waves, they consist of alternate crests and troughs. The crests of the folds are termed *anticlines*, while the troughs are called *synclines*. This is shown in Fig. 219, where the up-folds *A* are the anticlines, and the down-folds *S*, the synclines. Even if through erosion the original crests should be carried away, and the whole reduced to a level surface *ll*, we should still term the *A* portions below the surface anticlines and the *S* portions synclines, and in imagination reconstruct the missing parts. This should make it clear that anticlines and synclines *are not a matter of surface topography, but of structure.* Although, as not infrequently happens, the original configuration of the surface may be reversed by erosion, as in Fig. 220, we should call the parts *S*, of the down-folds still left, synclines, and the up-folds between, anticlines, and infer the underground structure shown. A natural section through an anticline is seen in Fig. 221, and one through a syncline in Fig. 222.

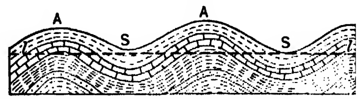


Fig. 219. — Diagram to illustrate anticlines, *A*, and synclines, *S*.

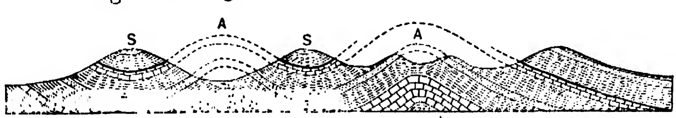


Fig. 220. — Anticlines, *A*, and synclines, *S*.

A simple mnemonic method, in regard to anticline and syncline, to enable the beginner to remember which is which, is to notice that the form of the letter A, the initial one of anticline, in itself represents a sharp-crested anticline.

Outcrop. — In considering the deformation of strata, only the simplest case has so far been presented, where they have been thrown into a series of simple, upright, regular folds. But, while this sometimes happens, it is usual to find the nature of the folding much more complicated than this, and there are also other things in regard to folds which are of importance, besides the consideration of a simple section across them. The varied kinds of deformation (or lack of it), which the strata have suffered in any region, condition the *geologic structure* of that region, and it is a matter of the

Fig. 221. — An anticline, broken at the top. In the foreground the outcrops of the eroded strata are seen dipping outwardly, from which the anticline structure could be inferred if the arch did not exist. Pembroke, Wales. Geol. Surv. of England and Wales.

highest importance, in several ways, as we shall presently see, that the geologic structure should be, so far as possible, known for every country. If the surface of the earth were everywhere naked bed-rock, this would not be, relatively, so difficult; but since it has been

Fig. 222. — A syncline, near Hancock, Md. C. D. Walcott, U. S. Geol. Surv.

greatly eroded, and is so covered with earth and vegetation, or water, snow and ice, the difficulties of the task have been enormously augmented. The manner in which we are able to discover the structure in a region is by a careful study and comparison of the *outcrops,* and by this term is meant those places where the underlying bed-rock comes to the surface and is exposed. See Fig. 221. If the ground were perfectly level and the strata horizontal, the outcrop would be the flat surface of a rock stratum, and we should learn little from it, beyond that fact. But if the ground is cut in any way, as by streams, we might be able to inspect the outcropping edges of the strata along the valley slope, as in Fig. 205. If the sides of the valley were trenched by ravines, the line of outcrop would not be straight, but sinuous, retreating from the valley into the ravines, and advancing on the spurs. See Fig. 223.

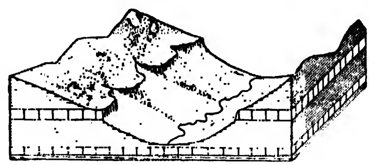


Fig. 223. — Section and outcrop of strata along valley.

If the strata have been inclined by folding, and eroded, it will frequently happen that the edges of the harder, more resistant beds *outcrop* in projecting rock masses, or reefs. In mountain regions, the higher up we go, the less soil there is apt to be, and the more outcrops, until eventually the rocky ridges themselves form vast outcrops. By study of the dip and strike of the outcrops of a region the geologic structure is determined.

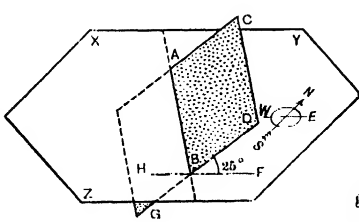


Fig. 224. — To illustrate dip and strike of strata.

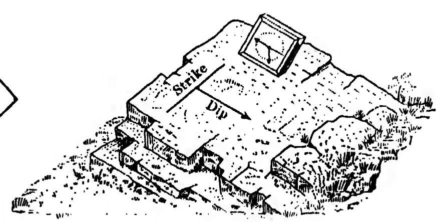


Fig. 225. — Illustrating outcrop, strike, dip, and determination of latter by clinometer.

Dip and Strike. — These terms may be defined as follows: *Dip is the angle of inclination of the plane of stratification with the horizontal plane. Strike is the direction of the line of intersection of the plane of stratification with the horizontal plane.* This may be illustrated by Fig. 224. Imagine *XYZ* to be the horizontal plane, and *ABCD* the plane of stratification of the inclined strata. Then the angle *DBF* = *HBG* is the dip, and the direction of the line *AB*, re-

ferred to north and south, is the strike. Since two planes could be passed through *AB*, one dipping to the left, as in the diagram, the other dipping to the right, with equal angles of inclination, it is customary to give the *direction of dip* to know which one is meant. Thus in a case like that shown in the diagram one would say, strike N. 30° W., dip 25° S. 60° W. Since the lines of direction of dip and strike are always at right angles, it is not really necessary to give the strike, if the direction and angle of dip are known; thus, dip 25° S. 60° W., would be enough.

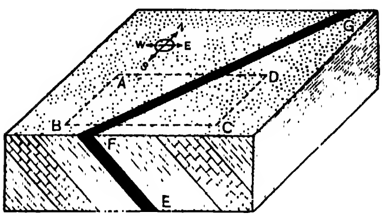


Fig. 226. — Use of dip and strike.

The direction of strike is taken with a compass furnished with sights, or whose containing box or bed-plate has straight edges aligned parallel to the NS points. The dip is taken with an instrument termed the clinometer, a pendulum swinging over a graduated arc, which measures the angle of inclination. The mode of use is shown in Fig. 225. For geologic purposes the compass and clinometer are usually combined in one instrument. The determination of dip and strike is not only necessary to unravel the geologic structure of a region, but has a practical use in other directions. Suppose that *ABCD* in Fig. 226 represents the boundaries of an area of land, which is known to contain a bed of coal, marble or valuable ore, represented by *EFG* for example, and for commercial or legal purposes it is necessary to give a description of the bed, and its exact position with reference to the property. The determination of its dip and the situation of its strike, with regard to the boundaries of the plot, furnish this position. The determination of dip and strike, when a reasonably good face of the strata is exposed, as in Fig. 221, is a comparatively easy matter, but where they are cut obliquely by erosion, and are on sloping hillsides, it is much more difficult; the plane of stratification must be conceived from the data furnished by the outcrop, and the desired results obtained by measurement of the imagined plane. If the strata are horizontal, they have, of course, neither dip nor strike; if they are vertical, the dip is 90°, the strike, the compass direction of the outcrop upon the horizontal plane.

Dip and strike are represented upon geologic maps by a conventional sign **T**, in which the direction of the cross bar, as placed on the map, indicates the direction of strike, while the upright leg points in the direction of dip. See Fig. 229. The length of the latter is also sometimes used to show the amount of dip; thus ⊢, with long leg, means a low angle of inclination, while ⊢, with short leg, a very steep dip; or the actual amount in degrees may be written in, thus ⊢ 30°.

Discussion of Folds. — Now that anticlines and synclines have been described, and the means by which these structures, which are generally more or less eroded, are determined in the field by study

of the dip and strike of the available outcrops, it is in order to further consider the nature and extent of folding. It is quite evident that a fold, up-arched, could not run in the direction of strike in-

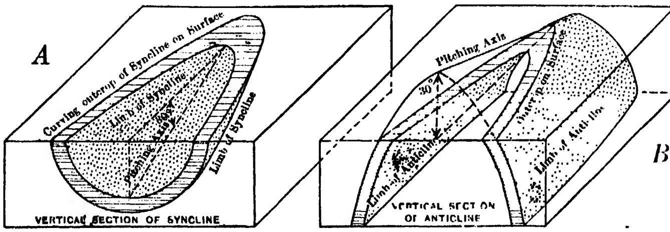


Fig. 227. — *A*, Ending of a syncline. *B*, Near the ending of an anticline. By H. H. Robinson.

definitely, or around the world; it must end somewhere. At the ending of a syncline we should have the structure seen in *A*, Fig. 227, and in *B*, that of an anticline approaching its ending, only a

Fig. 228. — On a plain of marine erosion the outcropping edges of the strata are seen at the ending of a syncline, as shown by the curving strike and inward dip. Near North Berwick, Scotland. Geol. Surv. of Scotland.

single stratum being shown in both. In the former the plane of stratification is warped into a form like the end of a boat; in the latter the boat would be overturned. It is evident that in both, the

strike of a hard projecting bed, as determined from its outcrops after the erosion indicated, would be elliptical, Fig. 228. The line of direction *xy* of the fold in Fig. 229 is the *axis* of the fold; in the syncline, at its end, this line *emerges* from the ground, in the anticline it *plunges* into it; the amount of inclination to the horizontal

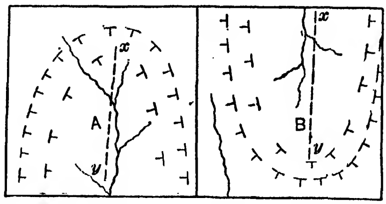


Fig. 229. — Map of dip and strike showing underground structure of *A*, a syncline and *B*, an anticline.

of this line as the fold dies out is called the *pitch* of the fold. See also Fig. 227. Considered in regard to their relative length and breadth, folds may vary from a dome-shaped uplift of the strata, whose strike would be circular, to extremely long narrow anticlines, whose strike is an elongated ellipse-like outline, and along whose sides the strike of the outcrops may be parallel for many miles, as in the Appalachian Mountains. And, of course, the same may be true, in reversed structure, for synclines.

Inclined, Unsymmetric and Broken Folds. — In the cases mentioned above we have considered simple, regular, upright folds. If

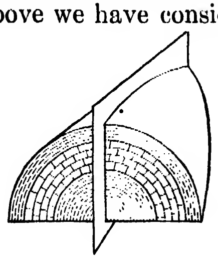


Fig. 230. — Upright symmetrical fold; axial plane vertical.

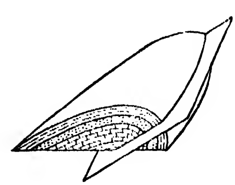


Fig. 231. — Inclined symmetrical fold; axial plane inclined.

through the center of a fold and its axis a plane be imagined to have been passed, as in Fig. 230, like the extended keel of a boat, we may term this the *axial plane* of the fold. In a regular, or symmetric fold, this plane is one of symmetry, that is, the parts to left and right of it are symmetrically disposed, or each point on the left of the plane has its corresponding point at an equal distance on the right of it. If the fold is upright the plane is vertical, Fig. 230. But it is very common to find that folds instead of being upright have

been pushed over as in Fig. 231 until the axial plane is inclined; in this case the fold is said to be *overturned.* Such overturning may, indeed, go so far that the axial plane is nearly, or actually, horizontal; and the fold is then termed *recumbent.* An example of an

Fig. 232. — An overturned and nearly recumbent anticline. Panther Gap, Va. N. H. Darton. U. S. Geol. Surv.

overturned anticline is seen in Fig. 232. Similar cases may happen with synclines.

It is also very common to find that folds are asymmetric (without symmetry), that is, they are not similar to right and left of the axial

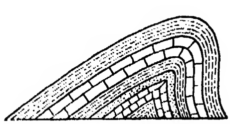


Fig. 233. — An asymmetric fold.

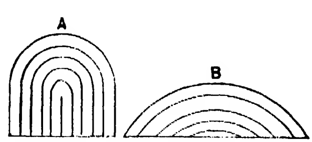


Fig. 234. — *A*, closed fold; *B*, open fold.

plane, which is not, therefore, one of symmetry, as in a regular fold. See Fig. 233. Such asymmetric folds may be upright, overturned, or recumbent, as with regular ones.

Finally, folds may be so sharply flexed (creased) that they may break to a greater or lesser degree, especially at the apex. And on breaking, the parts are liable to be displaced with respect to one another, or faulted. Faulting, however, is so important a phenom-

enon that it deserves especial consideration, which will be given to it in a later place.

Other Features of Folding. — In addition to the important general characters of folds described above there are some others, which, at times and in places, are of such interest that they deserve mention. Thus, when folds are so sharply flexed that the side limbs are in contact, as in *A*, Fig. 234, they are said to be *closed;* in this case the horizontal distance across the strata, or the width of the fold, cannot be further reduced without squeezing or mashing of the beds; when not in contact, as in *B*, they are said to be *open*

Fig. 235. — Outcrop of strata show as in *a;* they might be one series with inclined dip, or they may be closed isoclinal folds and receive various explanations, two possible ones being shown in *b* and *c*.

and the strata may be further folded without mashing. An example of a closed fold is seen in the overturned anticline, Fig. 232; a diagram of open, upright anticlines in Fig. 220.

In *isoclinal* (equal inclination) folds the strata are compressed until, on both sides of a fold, and perhaps throughout a series, they are parallel and have the same dip, Fig. 235, *b* and *c*. When such folds are cut away by erosion as in *a*, they may form structures very difficult of interpretation.

For a series of strata with a more or less uniform dip, the original structure of which for any reason is in doubt, Daly has proposed the term *homocline,* which is defined as any block or mass of bedded rocks all dipping in the same direction.

In what has been said so far of folds they have been treated as simple structures with true axial planes. But folds are frequently warped or bent, so that the flat axial plane of the regular fold is also warped or bent, not only in vertical, but also in about horizontal directions. Folds may also branch or be compound, and thus a variety of most complicated structures be induced. And this is true both of anticlines and synclines. See Fig. 236.

Sometimes in the elevation of portions of a country, as in the Plateau region of the Southwest, the strata are flexed as shown in Fig. 237. This is known as a *monocline*. Strictly defined, it is a one limb flexure, on either side of which the strata are horizontal or have uniform gentle slopes. True monoclines are uncommon, and many that have been described as such are, in reality, very asymmetrical anticlines.

Geosynclines and Geanticlines. — It has been previously mentioned, page 251, that long narrow belts of the ocean floor near the continental masses form concave tracts from 100 to 200 miles broad.

These down-warps of the earth's crust are evidently on a vastly greater scale than the folds we have been considering and which appear as mere minor and superficial wrinkles in comparison. Such

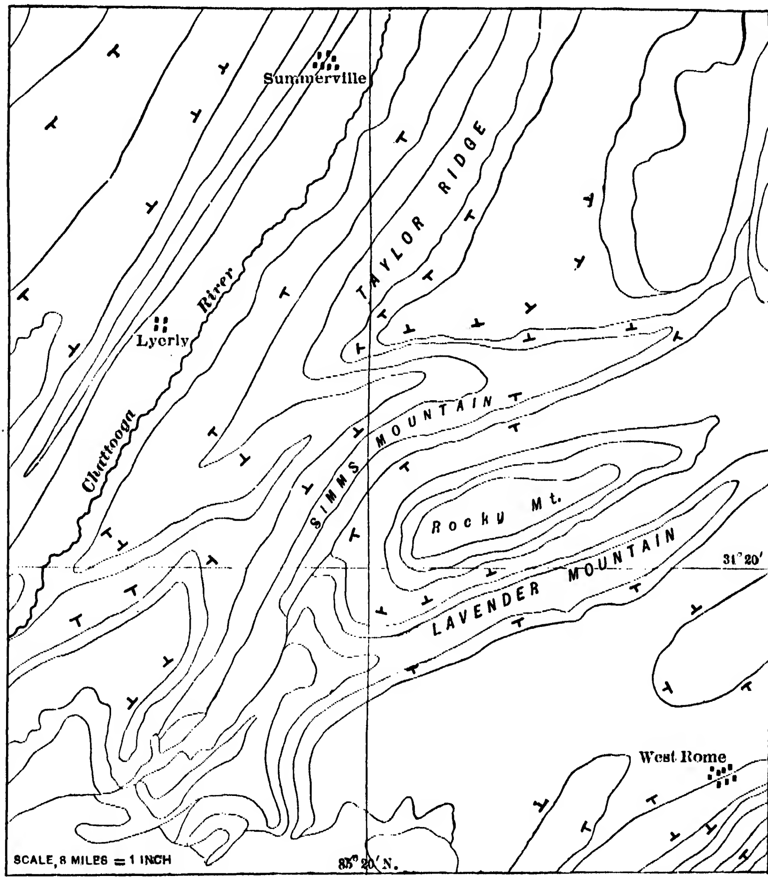


Fig. 236. — Map of an area near Rome, Georgia, showing warping, branching, and ending of folds, both anticlines and synclines, by the ridges and lines of outcrop of strata on the surface. Rome Folio, U. S. G. S.; C. W. Hayes.

great down-warps, which may be 1000 miles long and 200 broad, have been termed *geosynclines* by Professor J. D. Dana. There are facts which go to prove that, correspondingly, there are broad uplifts which are called *geanticlines*. The prefix is from the Greek word signifying the earth, to emphasize the scale of the phenomena. Such up- and down-warps may occur on the continents, as well as on the ocean floor. Thus the basin of Lake Superior has been held to represent a geosyncline, while the country northeast of it, in

Canada, extending to Labrador, is believed to be a low, wide, slowly rising arch, which may represent a geanticline (see page 240). In the region about Cincinnati there is also a wide flat arch which forms a geanticline.

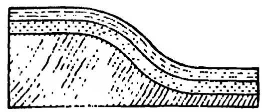


Fig. 237. — A monoclinal fold.

The geosynclines of the past, as well as those of the present, have been the great basins for the accumulation of sediments, like those which now form the Appalachians and the Alps. When later, by actions which we shall study more in detail under mountain ranges, the accumulated beds are uplifted and compressed into folds, the whole series of folds, referred to the plane of the horizon, may form a compound, uplifted mass, which erosion thereupon carves into a

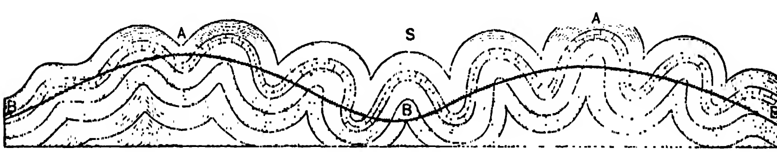


Fig. 238. — To illustrate terms used in compound folding. The general uplifted masses of folds *AA* are called anticlinoria, while the down-warped mass of folds *S* is termed a synclinorium. The general average warping effect of the folding is indicated by the line *BB*.

mountain range with the aspect familiar to us. Such a mass of strata, laid down in a geosyncline and crushed by folding into a mountain range, has been termed by Dana a *synclinorium* (from syncline and oros, Greek for mountain).

The term thus introduced by Dana has, unfortunately, been diverted from its original meaning, and applied to a general syncline compounded of minor folds and contrasted with *anticlinorium;* see Fig. 238. It has thus become a term of structure, and the related idea of mountain-making, which the name expresses, has been relegated to a subordinate position, or entirely left out.

Unconformity and its Meaning

Definition. — It is not uncommon to find, on examining the stratified rocks exposed in outcrops in cliffs, valleys, and mountain sides, that one set of beds, whose parallel position, kinds of rocks and their relations, and contained fossils prove them a continuously deposited series, are resting upon another set of rocks, whose position and characters show equally well that they were

formed at another period and under other conditions. Thus in the diagram, Fig. 239, the layers of strata *d* have been deposited at one period and under one set of conditions; they are, therefore,

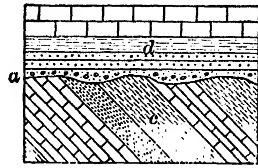


Fig. 239. — Section to show unconformity. A conformable set of strata *d* rest unconformably upon another conformable set *c*; the surface *ab* is the unconformity.

spoken of as a *conformable* series of beds, or a formation. Also the series of beds *c* are conformable among themselves; but it is quite evident that they are not conformable with *d*. To be in the position represented, events have happened to them which have not happened to *d*. The two series are unconformable with respect to one another, and the surface

Fig. 240. — Angular unconformity. Basal Wasatch conglomerate resting on upturned and eroded Laramie sandstone. Near Meeteetse, Wyo. C. A. Fisher, U. S. Geol. Surv.

ab separating them is called an *unconformity,* see Figs. 239 and 240. It is not intended by this statement that one should infer that the lower rocks, upon which the upper series of strata unconformably rests, should necessarily also be stratified, or sedimentary ones. The lower formation might be composed of igneous rocks, such as granite for example, or it might be composed of metamorphic ones, such as schists of various kinds, but the line

ab would still exist and would be an unconformity. This will be better understood when we consider the geological history which an unconformity reveals.

Geological History Revealed. — Let us take a case like that shown in Fig. 241, as an example. In this the following geological events are recorded. First, a period of quiet deposition in which the beds of the set *c* were laid down in horizontal position, or nearly

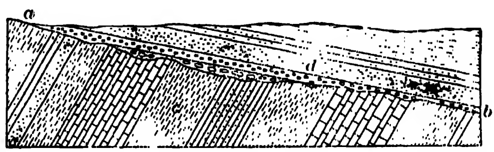


Fig. 241. — Angular unconformity; both series of beds tilted.

so. The thickness of the beds, the kinds of rocks, their characteristic features, and the contained fossils constitute the record for this period. Next, a time of elevation when the sea-bottom became a land surface, accompanied by tilting of the strata, and followed by an interval when the uplifted strata were deeply eroded. For this period of uprise, tilting, and erosion we have no means of estimating the duration, except by the amount of erosion and by the record of succeeding events which mark its end. Not only were there no records formed, in the shape of sediments, etc., but those of the previous period were wasted and more or less lost by erosion. There is, therefore, a gap in the geological record at this point, and it is consequently often spoken of by geologists as a "*lost interval.*" Next in the geological history followed a period of subsidence, when the eroded surface became sea-bottom again, and received a new deposit of sediments, forming the conformable series of strata *d* in our diagram. The events of this time are again recorded in the strata as before. And finally, after a second period of uplift and tilting, the whole course of events is presented to us to be read as erosion progresses. The history here given may then be summarized as follows: first, deposition of strata; second, elevation and erosion; third, subsidence and fresh deposition; fourth, final elevation. And as a corollary we may add, and this is the important point about the matter, that, *an unconformity always represents a former more or less eroded land surface.*

Relation of an Unconformity to Kinds of Rocks. — Since an unconformity represents a submerged land surface, it is of interest to consider the kinds of rocks that would naturally be associated with it. Evidence appears to prove that subsidence takes place slowly and, usually, with more or less

varying pauses in the process. As the land lowers, the sea works its way inward, due both to submergence and to its own ceaseless gnawing at the coast-line. Where the land and sea meet there is generally a *beach,* and, as the land subsides, this beach marches inland at the edge of the encroaching sea. Every part of the newly made sea-bottom will have been passed over by this advancing beach. But the beach is that part of the bottom which is subjected to the ebb and flow of the tides, and to the onward rush of the waves and their returning undertow. Consequently, it is exposed to the action of strong currents, and only the coarsest of sediments, gravels and coarse sands, can compose it. As the land subsides, all its superficial deposits, earth, stones, and rock decayed by weathering, will be worked over by the advancing sea, down to bed-rock, and perhaps deeper, and converted into beach material. The finer particles of the ground-up detritus will be swept

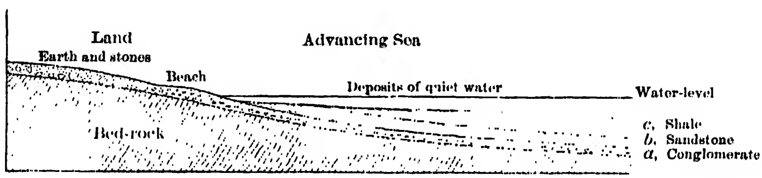
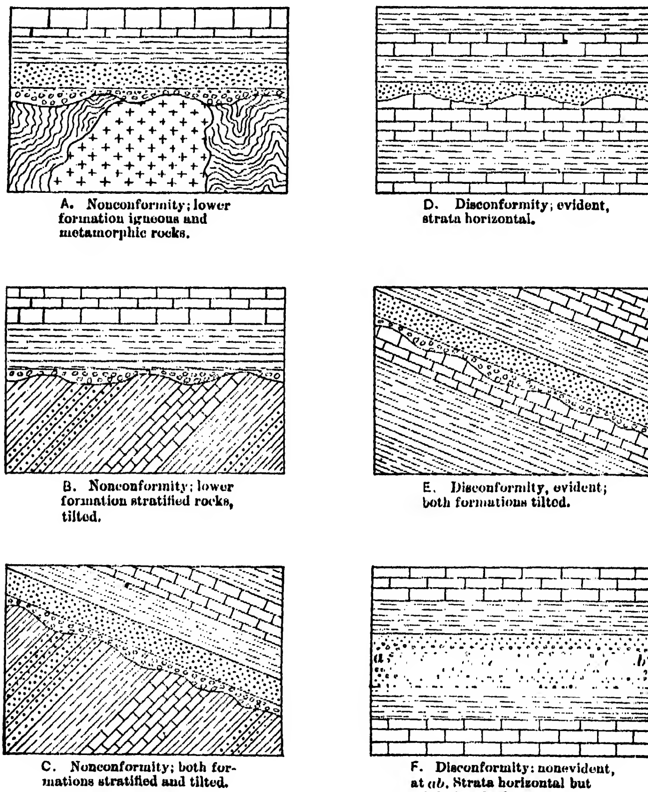


Fig. 242. — Diagram illustrating the normal order of deposits above an unconformity

out to sea to be deposited in quieter waters, and will form fine silts and muds. If one now imagines this state of affairs gradually passing inland, it is evident that the *first rock stratum of the new series, lying unconformably on the old bed-rock of the previous formation, will be a conglomerate or coarse sandstone,* since this is the consolidated form of the gravels and sand of the beach. Above this we should expect the fine deposits of quiet water to appear as finer sandstones and shales, representing the silts and muds, succeeded or interspersed with marine deposits of limestone. These relations are shown in the diagram, Fig. 242. Normally, then, we should expect an unconformity to be marked by the presence of a conglomerate (or coarse sandstone), and this is often the case. While the above is the theory, it is evident that in practice, the result must depend largely on the nature of the disintegrated land material supplied to the waves and currents, and the extent to which they can operate on it. The theory presupposes that the material is of unlike sizes and hardness, to obtain the variation in the beds. But, if the land should consist of strata of soft and homogeneous character, for example, as seen in areas composed of clays or shales, fine even-grained sediments might be formed which would yield no basal conglomerate. In the level interior regions of North America, the flat-lying beds contain many unconformities which are not separated by conglomerates.

It is evident that, if the process discussed above were to be reversed, and the sea-bottom to *rise,* instead of to sink, the formations would also be reversed, and the sea-beach would be the *last* deposit left on the surface of the newly made land. If we should imagine this compacted into rock, it would form a conglomerate of *emergence,* as contrasted with the one of *submergence,* described above. Being the first part of the new land to be attacked by erosion, and being still soft and unconsolidated, it would be the first material to be carried away and to disappear. Hence conglomerates of emergence are

not apt to be found. But in small oscillations of the surface of land at, or near, sea-level, a conglomerate of emergence might persist long enough to be subsequently covered by the one of submergence. The two might then form, apparently, a single bed of conglomerate, through which would run the line of unconformity, which might thus be non-apparent. This would furnish a case of what we might term a slight unconformity. Owing to the difficulty of detecting them, such conglomerates of emergence are apt to be overlooked where they might occur. This point will be referred to later.



A. Nonconformity; lower formation igneous and metamorphic rocks.

D. Disconformity; evident, strata horizontal.

B. Nonconformity; lower formation stratified rocks, tilted.

E. Disconformity, evident; both formations tilted.

C. Nonconformity; both formations stratified and tilted.

F. Disconformity: nonevident, at *ab*. Strata horizontal but might be tilted.

Fig. 243. — Diagram illustrating various phases of unconformities.

Classification of Unconformities. — These may be divided into two main groups. In the first, the lower formation, either by the tilting of the beds or by its being composed of non-stratified rocks, shows at once its non-conformity with the series of beds above it. This kind is illustrated by the diagrams (Fig. 239 and 241) previously given. It is sometimes called an angular unconformity (see Fig. 240), because the stratification planes of the two series are

at an angle; this term is good so far as it goes, but it does not cover the whole case, since, as mentioned above, the lower formation is not always composed of stratified rocks with distinct stratification planes, but may be of igneous or metamorphic rocks, which do not show them. A more general term is needed, and an unconformity of this class is here termed a *nonconformity*.

On the other hand, it may happen that the lower formation will be elevated, eroded, and submerged without material disturbance of the position of the beds. In this case the old and the new formations will have their stratification planes actually, or practically, parallel. This constitutes an unconformity of the second class, and, as it is desirable for a number of reasons that it should be distinguished from one of the first class, it has been termed a *disconformity*. Further, it may be that the erosion line between the two formations is an irregular one, and thus clearly visible; this may be termed an *evident* disconformity. Or, owing to circumstances, the erosion line may run parallel with the strata and not be apparent; the unconformity must here be determined by the sudden change in the nature of the fossils and by other things, such as the occurrence of thin basal sandstones and conglomerates, etc. (See in this connection what has been previously said regarding conglomerates of emergence.) In contrast with the previous one a case of this kind can be called a *non-evident* disconformity. We have, then, the following cases of unconformity:

Unconformity.

1. Nonconformity, two formations visibly different.
   a. Lower formation of rocks non-stratified, or apparently so.
   b. Lower formation of stratified rocks, tilted.
2. Disconformity, two formations in parallel position.
   a. Evident, erosion line clearly visible.
   b. Non-evident, erosion line not visible.

These different cases are illustrated in Fig. 243.

Also it may be added that in importance, in the length of time represented, in the greatness of change of life indicated by the fossils, and in the interest and variety of events recorded, the unconformities, in a broad general way, diminish from top to bottom of the diagram from A to F. Disconformities are usually ascertained on the basis of marked changes in the faunas or in the sedimentation. There are, however, many short breaks in the sedimentary record, due largely to oscillations in the intensity of climatic factors. In the aggregate their time value is large. These small breaks Barrekk has called *diastems*.

CHAPTER XII

THE IGNEOUS ROCKS

The igneous form a second great division of the different kinds of rocks which make up the crust of the globe. As their name implies, the presence of heat is an essential factor in their origin, and they may be defined as those rocks *which have been formed by the solidification of molten masses from within the earth.* Such molten masses, as has been mentioned under volcanic action, page 200, are commonly called *magmas,* a term we shall frequently use in speaking of them. These rocks are sometimes referred to as *primary,* because the material which composes the other kinds was originally derived, either from them or from the original shell of the earth, which many regard to have been of the nature of igneous rock.

Distinguishing Characters. — The features of igneous rocks by which they may be distinguished from the sedimentary ones, whose characters have been given in preceding pages, and from the metamorphic ones to be presently described, consist partly in the relations which the masses exhibit towards other rocks and which we may term their mode of occurrence, and partly in characters which become evident when a rock mass, or a piece of it, is closely examined. The different modes of occurrence of the igneous rocks will be described in the following section; with regard to those more minute features which are seen on close examination, the following are of importance. The igneous rocks do not, of course, contain fossils, nor, as a rule, do they show the parallel or banded appearance of the stratified rocks, for, in general, a surface in one direction looks like a surface in any other direction. They also have certain peculiarities in the minerals composing them, and in the arrangement of these mineral grains (the *texture,* so-called), which distinguish them. Sometimes, indeed, they are more or less made of glass, which at once betrays their origin, since this substance could be formed only by the chilling of melted material. These features will be more fully described when the different kinds of igneous rocks and their classification are considered; we will first discuss the various ways in which masses of igneous rock occur.

Occurrences of Igneous Rocks

Intrusive and Extrusive Rocks. — There are two chief modes of occurrence of igneous rocks, the *intrusive* and the *extrusive*. In the former the magma, rising from depths below, has stopped before attaining the surface and has cooled and solidified, surrounded by other rock masses of the earth's outer shell. In the extrusive, the magma has attained the surface, come out upon it, and there solidified, forming the rock masses. These are sometimes called *effusive* and sometimes *volcanic* rocks, though it is held by some that they are not always connected with volcanoes. See page 221.

It should be understood that, although the division of igneous rocks into intrusive and extrusive is a natural one, the two are closely connected and, in fact, pass from one into the other. The magma forming every extrusive mass has come through some passageway below, which has remained filled, and, eventually, solidified into rock. There is thus a prolongation of every extrusive body above, into an intrusive one below. In some cases this connection of the extrusive with its root below may be seen, but, more generally, the extrusive covers it, or has been separated from it by erosion, and the rock continuity has been lost. It is clear also that we must conceive the intrusive prolongation as passing downward into some greater mass of magma (or rock) below, of a nature to be presently described. See also, in this connection, what has been said regarding the relation between volcanoes and deep masses of magma, page 200.

With both intrusive and extrusive rocks there are variations in the mode of occurrence depending, in the case of the former, on the relations an intrusive mass may bear to the other rocks which enclose it, and in the extrusive on the conditions under which the magma was ejected. Following the course of the magma upward we will begin with the intrusive; but it should first be recalled that, since these rock masses were covered by previously existent ones at the time of their formation, they can only be exposed at the surface, and thus laid open to observation, after a period of erosion sufficient to carry away the cover and disclose their intrusive relations. In some cases, when intruded near the surface, this time interval may have been a comparatively short one; in other cases very prolonged, when the masses were deeply buried.

Intrusive Modes of Occurrence. — These are *dikes, intrusive sheets, laccoliths, necks, stocks,* and *bathyliths.* Several other modes of occurrence have been described and named, but as they have not yet been generally recognized as of the importance of those mentioned, they will, for simplicity's sake, be treated as modifica-

tions of them. The simplest form of intrusion is that of the dike and this will be considered first.

Dikes. — A dike results from the simple filling of a fissure in existent rocks by molten magma from below, which there solidified. Consequently, its extension in length and breadth is great compared with its thickness. It may "cut," that is, pass through, rocks of any kind, igneous, sedimentary, or metamorphic; but in the sedi-

Fig. 244. — Dike of trap-rock in granite. In this case the dike is less resistant and has been cut away by erosion, leaving a trench in the granite. Isles of Shoals, N. H.

mentary it must traverse the planes of stratification at an angle; if parallel to them, it is an intrusive sheet. As exposed on the surface it may be a few yards, or many miles, long; it may be a fraction of an inch, or many hundreds, or even some thousands of feet in thickness. An illustration of a dike is seen in Fig. 244.

The ordinary thickness of most dikes is from two or three feet up to twenty; the exposed length very variable. The course of a great dike in the north of England has been traced for over 100 miles. As we naturally think of a bed of stratified rock as in a horizontal position and call its departure from horizontality its dip, so we think of a dike as a sheet of rock in a vertical position; this is by no means always the case, and the angle of inclination of the plane of extension of the dike with the vertical is called its *hade*. The direction of its outcrop, or intersection with the horizontal plane, is termed its strike, or *trend*.

Dikes may have attained the surface and given rise to outflowings of lava, or they may not have reached it, but have been exposed by later erosion. In some cases they have formed the canals feeding larger intrusive bodies above

them, such as the sheets and laccoliths to be next described. In the process of erosion, it sometimes happens that the dike is more resistant than the surrounding rocks and is left projecting as a wall; sometimes less resistant and has become a ditch; from these features the name is derived, especially the more prominent wall, for dike means both wall and ditch. The rock of a dike is cut into blocks by fissures, and very commonly the blocks are columns lying perpendicular to the wall of the dike, like a pile of cordwood, an arrangement whose origin is described later under columnar structure. Dikes occur in many places in more or less well-defined systems, and around volcanic centers are apt to be radially disposed.

Fig. 245. — Intrusive sheets of igneous rock. Cottonwood Canyon, New Mexico. W. T. Lee, U. S. Geol. Surv.

Intrusive Sheets. — It is not uncommon to find, where intrusions of magma occur in stratified rocks, that it has been forced in layers between the beds. This most frequently happens where the beds are weak and easily penetrated, as in shales, thinly bedded sandstones, and the like. Such a flat extended mass lying concordantly along the planes of stratification is known as an *intrusive sheet* of igneous rock, though sometimes it is spoken of as a *sill*. Such sheets may be a foot or so in thickness, or several hundred feet, and they may spread over many miles in area. An illustration of them is seen in Fig. 245.

Sheets may break dike-like across the strata and be continued along a new horizon. These intrusions may be distinguished from surface flows of lava, which have been buried by deposits of later sediments, by the rock composing them being of the same hard firm nature at top and bottom, and by the overlying sediments being baked and altered by the intrusion. The surface of a

lava flow is usually spongy, ropy, slaggy, etc. (see page 205), and a flow could, of course, exert no action on beds not yet deposited upon it. Intrusive sheets are most liable to occur where larger, more important intrusions of magmas, such as laccoliths and stocks, have taken place, as accompanying features in the surrounding strata. In regions where thick intrusive sheets occur, and the strata have been broken, dislocated and upturned by faulting (see faulting), they may give rise to prominent topographic and scenic land features through the effects of later erosion. This is illustrated in some of the trap ridges of southern New England, northern New Jersey, and in other places.

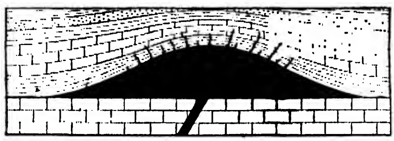


Fig. 246. — Section of a laccolith. The black area is the igneous rock.

Laccoliths. — The laccolith in its typical development is a lenticular or dome-shaped mass of magma intruded into the sedimentary rocks between the bedding planes. It has a flat floor, and is more

Fig. 247. — Bear Butte; a laccolith denuded of its cover and the igneous mass laid bare. The ring of upturned eroded strata is seen about its base. Black Hills, South Dakota. N. H. Darton, U. S. Geol. Surv.

or less circular in ground plan. If the supply of material in the formation of an intrusive sheet is more rapid from below than can easily spread laterally, the strata above will be uparched, as if by a hydrostatic press, and a thick lens of liquid rock will be produced, giving rise on solidification to a laccolith. The name is

from the Greek, meaning cistern-rock. Such a mass may be a few hundreds of feet or a mile thick at the center, and a few hundreds of yards or several miles in diameter. In the uprise, the sedimentary beds above are usually more or less stretched, thinned, and broken. A section of a laccolith is shown in Fig. 246, and a photograph of one from which the cover has been removed by erosion, laying bare the mass of igneous rock, is seen in Fig. 247.

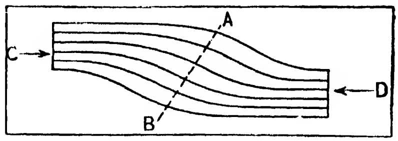


Fig. 248. — Strata being folded by compression *CD*, relief from pressure from overlying beds and spreading might occur in direction *AB*.

While the above statement gives the idea of a typical laccolith, many departures from this arrangement are found in the actual occurrences. In ground plan they may be circular, oval, or quite irregular, and instead of being symmetrical in section, as in Fig. 246, they may be one-sided, or wedge-shaped. According to their degree of flatness, all transitions into intrusive sheets occur. They may also break across the strata in places like intrusive sheets. They may thin out into intrusive sheets, or be accompanied by them on the flanks of the arches, and thus be compound in structure. Such sheets may themselves swell out into inclined lenticular masses, or subordinate laccoliths. And in regions where strata are being folded, areas of relief from pressure or, possibly, openings might form on the sides of the arches, see Fig. 248, which would permit the entrance of magma. This would give rise to inclined,

Fig. 249. — Section of an inclined laccolith, or phacolite.

doubly convex bodies like that shown in Fig. 249. Laccolithic bodies of this character have been termed *phacolites* by Harker (from the Greek words for lentil + stone). It is sometimes questioned whether the magma supplies its own force in making the intrusion and in arching up the strata, or in other words is *aggressive*, or whether, as indicated above, the force lifting the beds comes in some other way, and the magma simply flows into the space opening for it, or the intrusion is, so to speak, *permissive*. But a study of the occurrences shows that in all probability both of these cases occur. In central Montana, where the strata are horizontal and undisturbed save by the intrusions, the magma must have acted aggressively, but in other places where folding and uplifts occur, the intrusions were probably permissive.

Laccoliths, more or less exposed by erosion, are conspicuous features in

many parts of western North America, where they were first discovered by Gilbert in the Henry Mountains in southern Utah. Some of the best examples occur in Colorado, as described by Cross, and they are also abundant in Montana. In places they are so aggregated as to make mountain groups. More recently they have been found in various parts of the world and thus appear to be a not uncommon form of intrusion.

Bysmaliths. — It may happen that an intrusion is so aggressive that what would otherwise probably be a laccolith may have its roof ruptured, and driven upward, by the magma rising like a plug through the strata. The vertical dimensions of such a mass may be much greater, compared with the lateral ones, than in a laccolith. A core-like intrusion of this character has been termed by Iddings a *bysmalith* (Greek, plug-rock).

Chonoliths, Etc. — Intrusions of magma may be of very irregular shape and bear no definite relation to the stratified beds in which they occur, as do

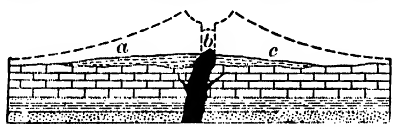


Fig. 250. — Section through a partly eroded volcano, with volcanic neck left projecting.

sheets, dikes, and laccoliths. They may be formed aggressively by the rising magma having ruptured and crowded aside the beds, or in regions of dislocated rocks by its having passively risen into irregular chambers. For all such irregularly shaped bodies of injected rock Daly has proposed the name of *chonolith* (from the Greek words meaning "mold," used in casting metals, and rock).

Also the term *ethmolith* has been suggested when the intrusive mass has a funnel shape, and *lopolith* when flattish and depressed, saucer-like, toward the center. But none of these special designations, except laccolith, has as yet acquired general usage.

Necks. — When a volcano becomes extinct, the column of magma, occupying the conduit leading to unknown depths below, may solidify and form a mass of igneous rock. Erosion may cut away a great part of the ashes and lavas of the cone, leaving this more solid and resistant rock projecting, as shown by the line *abc* in Fig. 250. Or, the level of erosion may descend into the rocks which form the basement on which the volcano is built, all of the ashes and lavas being swept away, and only this mass being left to mark its former site. Such a mass of rock is known as a *volcanic neck*, and a view of one may be seen in Fig. 251. It is commonly more or less circular in ground plan and may be from a few hundred yards up to a mile or more in diameter. The rocks about volcanic necks are apt to be fissured and filled with dikes, and in many cases, if stratified, with intrusive sheets. The significance of volcanic necks has been previously explained, page 215.

Stocks. — This term has been applied to large bodies of intrusive rock which, in the form of magma, have ascended into the upper region of the earth's crust, and there solidified. They have become visible only by extended erosion, and usually have a more or less circular or oval ground plan. Their outer surface, or plane of contact, cuts across the inclosing rocks, is more or less irregular, and the mass may widen in extent as it descends. Their size may be from a few hundred yards to a number of miles in diameter. Since they are apt to form protuberant topographic features through

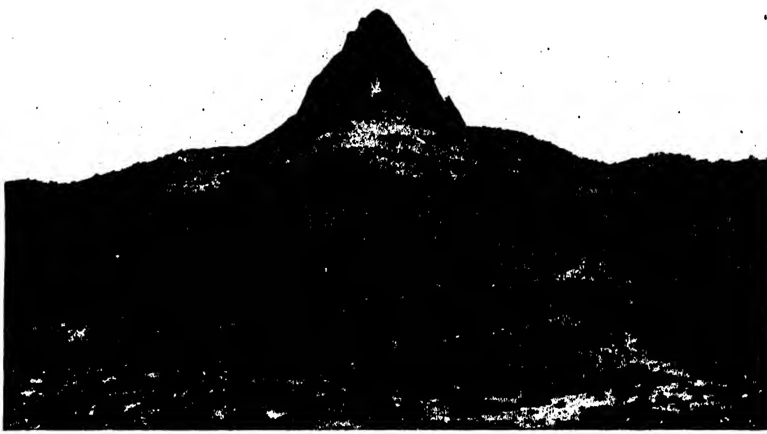


Fig. 251. — Alesna volcanic neck, Mt. Taylor region, New Mexico. C. E. Dutton, U. S. Geol. Surv.

erosion, they are sometimes, especially in Great Britain, called *bosses*. The distinction from a volcanic neck is not one of size alone, though necks tend to be smaller than stocks, but in that the term "neck" is employed only when there is evidence that extrusive volcanic activity has been connected with it. Some stocks were doubtless necks, but this cannot now be proved. The granite hills of New England, and of many other old eroded mountain regions are often largely composed of stocks, or bosses.

Bathyliths. — This word is used in a general way to designate huge irregular masses of igneous rock, which, underlying the sedimentary and so-called metamorphic ones, or sometimes cutting through them, have been exposed by erosion. They are seen in the oldest exposed areas of the earth's crust, where they are characteristically accompanied, or surrounded, by metamorphic rocks, as in

eastern Canada and New England, or in mountainous regions where they form the central cores of masses of the ranges, as in parts of the Rocky Mountains. They differ chiefly from stocks in their much greater size, as they are in some cases exposed over many thousands of square miles of surface.

Although some stocks are clearly intrusive, and have displaced the rocks whose site they occupy, the mode of formation of others, and of bathyliths, is still a subject of speculation. Some have held that they have attained their position by melting and assimilating the previous formation and thus replacing it, while others have urged the view that it has been ruptured, uplifted, and driven out by the invading mass of magma, and then eroded away. Various modifications of these views have been suggested, and while geologic science is not yet in a position to pronounce definitely upon their correctness, it seems probable that no one set process will explain all cases, and that at different times and places diverse agencies have operated.

Extrusive Igneous Rocks. — The modes of occurrence of the extrusive igneous rocks have already been described in connection with volcanoes and extrusions of lava, and what has there been said in regard to them may be profitably consulted in this connection, page 203. For the sake of convenience the following summary is here given. There are two kinds of extrusions of magma, depending on the quantity and activity of gases contained in it; the *quiet*, in which it outwells as a liquid and solidifies into rock, and the *explosive*, in which it is more or less violently driven into the air and falls in the form of solid fragments.

Quiet Eruption: Lava Flows. — Magma which appears at the surface and outpours is known as *lava*. When solidified it is commonly spoken of as a lava flow, or extrusive sheet. Usually such outflows are in connection with volcanoes, the extrusions of a few volcanoes being, indeed, wholly of this nature, like some of those in Hawaii, but generally lava flows succeed, or alternate with, projections of fragmental material.

In other cases it has been thought that they are not connected with volcanic eruptions, but have taken place as quiet outwellings from numerous fissures. This has sometimes occurred on a huge scale, as in the Columbia River region of the northwestern United States, in western India, and in the north of the British Isles. In the first two regions the repeated lava flows are thousands of feet in depth, and cover areas of from 100,000 to possibly 200,000 square miles. This view of the origin of the Columbia lavas has, however, been disputed, as mentioned on page 221.

Not infrequently sheets of lava have sunk below sea-level and been covered by deposits or they have originated on the sea-floor and have been covered. Such buried extrusive sheets are distinguished from intrusive ones by the fact that they have not altered, changed, or baked the sediments above them, and

their upper surfaces usually show the structures common to the surface of lavas, such as the vesicular, scoriaceous, and ropy ones described previously.

Explosive Eruption: Tuffs and Breccias. — When magma attains the surface in the canal of a volcano, it may give rise to quiet flows of lavas as mentioned above, or, if its viscosity is sufficient and it is charged with vapors under great tension, it will give rise to explosive activity, and the material will be projected into the air to fall in solid fragmental form, as already described under volcanoes, page 212. Owing to the expansion of contained vapors, chiefly steam, the projected pieces usually have a more or less vesicular structure, and vary in size from large blocks to fine dust. According to size this material may be roughly classified as follows: pieces the size of an apple and upward are termed *volcanic bombs;* those the size of nuts, *lapilli;* of the size of small peas, or shot, *volcanic ashes;* while the finest is *volcanic dust.* The coarser material, the bombs, ashes and lapilli, falls around the vent and builds up the cone; the lighter ashes and dust, carried by air currents, tend to fall after these, and at greater distances. The beds of coarser material thus produced are termed volcanic conglomerate, or, more commonly, *volcanic breccia,* while the finer material is known as *tuff.* See pages 208 and 213.

Volcanic Tuff. — The rock formed by the consolidating of volcanic ashes and dust is usually light in weight, sometimes of a chalky consistency, sometimes quite hard and dense. It is of various colors, generally of light shades. When very fine and compact a tuff might be mistaken for the rock of a lava flow, but generally examination will show angular fragments in it, and in some cases the tuffs contain excellent imprints of fossils; of leaves, twigs, etc., if the ashes have fallen on land, or of marine organisms, such as fishes, etc., if into water. If the ashes fell into water the tuffs may be well stratified and interbedded, perhaps with shales and sandstones. Or, volcanic ashes may be washed down into water, and, mingled perhaps with the ordinary products of land waste, give rise to a well bedded sedimentary series of strata. It is here that gradations of igneous into sedimentary rocks may occur. Volcanic tuff was formerly called *volcanic tufa,* but it is now customary to restrict the word tufa to deposits from aqueous solution, especially those of a calcareous nature. See page 167.

Volcanic Breccia. — This has a base of tuff more or less filled with angular pieces and bombs, and masses which are apt to be rounded. It often contains fragments of the rocks through which the conduit has been drilled. These characters distinguish breccias, even when they are very hard and much changed by certain processes which act upon rocks. Usually, they are rather soft and easily attacked by erosion; the cement, or base, goes first, leaving the bombs and contained masses projecting. In this way on the edges of cliffs oddly shaped figures of erosion are produced, in regions where volcanic breccias are common, as in parts of the Rocky Mountains.

Tuffs and breccias are rocks of wide distribution, being found in all those districts where volcanic activity is being, or has been, displayed, and their presence is, indeed, one of the surest indications of its occurrence in former times in places where vulcanism has long since died out. We are thus able to recognize the former existence of volcanoes in various parts of the eastern United States and Canada, from Nova Scotia to Georgia. In the regions of the Rocky Mountains they are found in vast quantities, piled up in places thousands of feet in thickness, where, as in western Wyoming, serried mountain peaks have been cut from them by erosion.

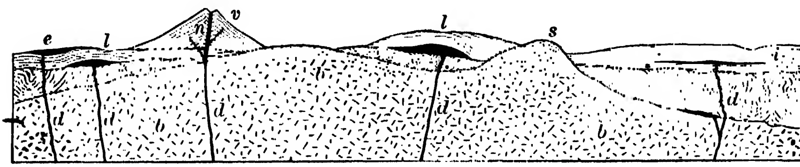


Fig. 252. — Diagram to illustrate the occurrence of igneous rocks: *b*, bathylith; *s*, stock; *n*, volcanic neck forming *v*, a volcano with tuffs and breccias; *l*, *l*, laccoliths; *i*, intrusive sheet; *e*, extrusive sheet; *d*, *d*, dikes. Horizontal distance shown thirty miles; vertical distance, three miles.

Age of Igneous Rocks. — The determination of the geologic period, when a given mass of igneous rock was erupted, or intruded, is made by observing its relations to the previously existent rocks with which it has come in contact. Thus, if one body of igneous rock, such as a dike, passes through, or cuts, another body of rock, it is the younger of the two. If it cuts across stratified beds it is younger than they are, and lavas, of course, are more recent than the rocks upon which they lie. If a sheet of igneous rock lying concordantly between strata has affected the beds both above and below (see contact-metamorphism, page 350), it is younger than both. If the overlying beds are not changed the sheet may be a lava flow, see page 315, and older than they are. It is thus usually easy to tell when an igneous mass is younger than other rocks by examining its contacts with them, but much more difficult to say when it is older than they are, because, usually, the younger beds have been eroded away if the mass is exposed, or they still conceal it, or it may never have been covered. The age of the stratified rocks is, of course, determined by their fossils, and the endeavor is made to bring the igneous ones, which contain no fossils, into time relation with them.

Kinds and Classification of Igneous Rocks

Introductory. — Those features of igneous rocks, by which the different kinds are distinguished, have been already mentioned in a

preliminary way in the discussion of the products of volcanoes, page 203, but should now receive the attention which they demand in this place. Igneous rocks are divided into different kinds on the basis of two properties, first, their *composition,* and second, their minute structure, or *texture.* Each of these requires explanation.

Composition of Igneous Rocks. — Since igneous rocks are produced by the solidification of magmas it is evident that their composition will depend on the chemical composition of these molten fluids. It has been already shown, page 201, that a magma consists of two parts, volatile constituents, which are given off as water vapor, carbon dioxide, sulphur fumes, etc., and a non-volatile part, a molten flux, consisting chiefly of the oxides of certain metals and silica. Although the gaseous part is important, for reasons we cannot now consider, in rock formation, it is essentially the melted oxides which give rise to the rocks and are the chief and determining constituents of magmas. While it is evident that a molten magma cannot be analyzed directly by chemical methods, still, the kinds of oxides present, and their relative proportions, can be ascertained by analysis of the cold and solid rock. This has been done with many thousands of igneous rocks from all parts of the world and, in a general and rudely approximate way, the following results have been obtained, which show the composition of the magmas.

Silica, SiO_2, always present; may vary from 35 to 75 per cent.
Alumina, Al_2O_3, varies from nothing to 25 per cent.
Oxides of iron, FeO and Fe_2O_3, usually both, 0–20 per cent.
Magnesia, MgO, 0–45 per cent.
Lime, CaO, 0–20 per cent.
Soda, Na_2O, 0–16 per cent.
Potash, K_2O, 0–12 per cent.

It must not be concluded from inspection of the above table that within the limits given, any and all sorts of mixtures of these oxides can occur. As we shall see presently, there are certain general laws governing their associations. It will also be noticed that there is one definite acid-forming oxide, silica, present, while the oxides of the six metals, aluminum, iron, magnesium, calcium, sodium and potassium, are, in general, bases. Since we have then an *acid* and *bases* in the magma, according to one of the fundamental principles of chemistry, there will be opportunity, under suitable conditions, for the formation of *salts.* What these salts are we shall learn later. Oxides of other elements occur in small or minute quantities, but are of so much less importance that they may be neglected.

Associations of Oxides in Magmas. — Although there are many exceptions to this rule, it has been found to be generally true that large percentages of potash and soda (alkalies) in a magma are

accompanied by correspondingly large ones of alumina and silica and by consequent small amounts of the other three metallic oxides. Conversely, large percentages of magnesia, lime and iron oxides are apt to be associated, and these go with low silica; the alumina and alkalies being small, or wanting. These reciprocal relations are of general fundamental importance in igneous rocks, and it will be recalled that they have been pointed out before, page 201, since the nature of volcanic activity, and the kinds of volcanoes, in large measure depend upon them. They may be expressed in a general way as follows:

Where SiO_2, Al_2O_3, $(Na,K)_2O$ are high, CaO, MgO, FeO are low or wanting.

Where CaO, MgO, FeO are high, SiO_2 is low, and Al_2O_3, $(Na,K)_2O$ are low or wanting.

Crystallization. — It is a familiar chemical experiment that, if one places zinc in sulphuric acid diluted with water, it will quickly disappear with evolution of hydrogen, and, in the place of the acid and the base (metal), the vessel will contain a salt, zinc sulphate, in solution. If the liquid be boiled down and concentrated to a certain point, the zinc sulphate can no longer remain in solution, but will begin to appear in solid condition in the form of crystals. If the hot solution be allowed to cool, more crystals of the salt will be formed, since, in general, hot solutions can contain more salt than cold ones. In analogy with what has been stated above, a molten magma is to be regarded as of the nature of a solution; it contains silica, an acid-forming oxide, and metallic oxides, which are bases. If the magma cools with sufficient slowness these will unite to form salts, which at proper temperatures will take on solid form and appear as crystals. This will proceed as the temperature falls until the whole magma turns into a mass of solid crystal grains. The molten liquid has become *stone*. It rarely happens that the proportions of acid and bases are so exactly balanced in a magma, or the circumstances are such, that it is completely turned into salts; nearly always there is an excess of the acid, which appears as solid silica, SiO_2 (quartz), or of some of the metallic oxides (iron oxides, alumina, etc.), which latter may combine. Such solid compounds, salts and oxides, occurring in nature are *minerals*, and we see from this that igneous rocks are, in general, composed of *mineral grains* of various kinds, and that these grains have crystallized from the magma.

Kinds of Minerals. — The more important of the minerals which form the igneous rocks are the following:

Feldspar Group	Ferromagnesian Group
Orthoclase Feldspar, $KAlSi_3O_8$	Mica (Biotite), $K_2(Mg,Fe)_2Al_2Si_8O_{12}$
Albite Feldspar, $NaAlSi_3O_8$	Pyroxene, $Ca(Mg,Fe)Si_2O_6$
Anorthite Feldspar, $CaAl_2Si_2O_8$	Hornblende, $Ca(Mg,Fe)_3Si_4O_{12}$
Nephelite, $NaAlSiO_4$	Olivine, $(Mg,Fe)_2SiO_4$
Also Quartz, SiO_2	Magnetite (Iron Ore), Fe_3O_4

Of these minerals, *feldspars, quartz, pyroxene,* and *hornblende* are the most important in forming igneous rocks and the student should, therefore, make careful note of them. For further details regarding them reference should be had to the Appendix dealing with the minerals mentioned in this work. It will be seen by examining their chemical formulas, as given in the table above, that they are composed of silica and the six metallic oxides previously mentioned as forming the magmas.

Furthermore, since it was shown that the relative proportions of the oxides varied in the magmas, it is evident that the relative quantities of the minerals will also vary. Thus, a magma in which $(Na,K)_2O$, Al_2O_3 and SiO_2 are the chief substances will form a rock consisting mostly of feldspars, while one in which CaO, MgO and FeO are high will make rocks containing largely or mostly pyroxene, hornblende and other *ferromagnesian* minerals, as they are called in allusion to the iron and magnesia in them, or mixtures of these minerals.

Thus it appears that igneous rocks vary in the kinds and relative amounts of the minerals which compose them, and on these variations, as we shall see later, depend mainly the different varieties of igneous rocks, and the manner of classifying them.

Texture. — While igneous rocks are distinguished and classified in one way by the *kinds* of mineral grains which compose them, they are also classified in another way by the *textures* which they may exhibit. By *texture* is meant the *relative size, or sizes,* of the component grains and their relation to each other. Thus, if the grains were as large as peas we should say that in texture such a rock was *coarse-grained;* if like ordinary loaf sugar, such a rock would be *fine-grained;* while, if the particles were so fine that they could not be discriminated by the eye and the rock appears like a homogeneous substance, we should say it was compact, or *dense,* in texture.

This evidently depends on the size of the particles, or crystal grains, and that in turn depends on the *rate at which the magma cooled.* For, if the magma is too hot, as explained above under crystallization, this process cannot take place, and no crystals will

begin to form until the proper temperature is reached; then they will commence to appear and, if the cooling is very slow, they will have time to grow to large size, giving a coarse-grained rock. But, if the cooling is rapid, new centers of crystallization will be more and more forced to form, and, if the process is thus hurried, instead of fewer crystals growing to larger sizes, the rock will consist of a much greater number of smaller particles, or will be fine-grained in texture. And with still more rapid cooling the particles may be so minute that the rock has the dense texture. Analogy will now

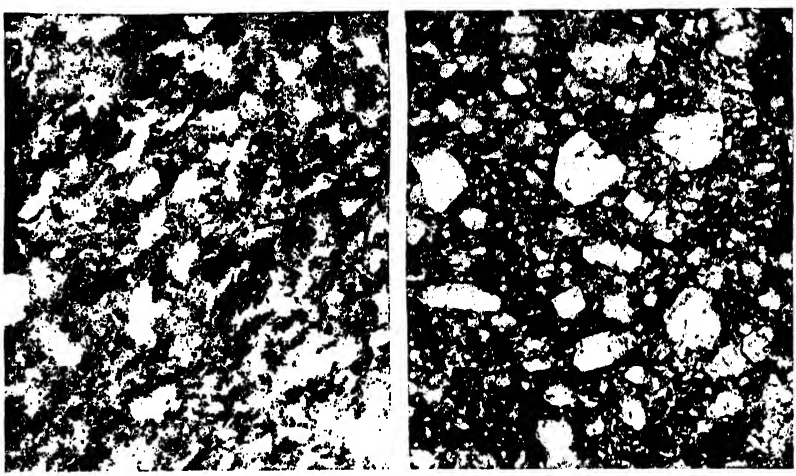


Fig. 253. — *A*. Even-granular Rock. *B*. Porphyry.

carry us one step more; we could conceive that the cooling might take place with such great rapidity that the magma would solidify into a homogeneous substance before any crystallization, which consists in the molecules arranging themselves together to form definite solid compounds, could occur. In this event we should have *glass*, or a glassy rather than a stony texture, as the result, a case which sometimes happens.

To sum up, then, we see that igneous rocks in their texture may be *coarse-grained*, *fine-grained*, *dense*, or *glassy*, and that this depends on the rate of cooling of the magma.

Porphyry: Porphyritic Texture. — In what has been said so far regarding the texture of igneous rocks, it has been tacitly assumed that the component mineral grains are, in any given rock, of uniform size, or that the rock is evenly *granular*, as it is called. This is, however, by no means always the case. For inspection of igneous rocks shows that in many cases they are composed of crystals of

two sizes; some larger and more distinct embedded in a matrix of much finer grains. An igneous rock having this latter texture is called a *porphyry*. Examples of the even-granular and porphyritic textures are seen in Fig. 253, *A* and *B*. The matrix of a porphyry is termed the *ground-mass*, and the larger embedded grains, or crystals, the *phenocrysts* (evident crystals). The porphyries are a large and important division of igneous rocks.

The ground-mass (matrix) may itself vary greatly in texture: it may be medium-grained, fine-grained, compact, or glassy; most commonly it is fine-grained, or compact. And the phenocrysts may also vary widely; they may be of large size, as large as walnuts, or as small as grains of sand; they may be abundant, or comparatively few. But always there is this *contrast* between *sizes* of crystals, between ground-mass and phenocrysts, which makes the essence of a porphyry, and the student should guard against making it a contrast of *colors;* thus a rock consisting of grains of light colored quartz and feldspar, in which are embedded a few black crystals of mica, all grains being of about the same size, is not a porphyry.

Relation of Texture to Geologic Mode of Occurrence. — Since, as has been shown above, the texture of an igneous rock depends chiefly upon the *rate* at which the magma cools, it is clear that this in turn will depend most largely upon its final resting place. For it is obvious that an *intrusive* mass of magma, surrounded and blanketed above by other, older rock masses, must lose heat much more slowly than an *extrusive* one, poured out on the surface in the form of lava. Hence, as coarse-grained textures mean slow cooling, we naturally associate them with intrusive masses, and, conversely, regard the dense, or glassy types as belonging to the products of extrusion, the surface lava flows. But it is also clear that the size of the intruded mass will have much to do with the rate of cooling, since a very large mass cools more slowly than a small one. Thus, the great bathyliths and stocks are naturally coarse in texture, whereas dikes and intruded sheets tend to be much finer, or compact. On the other hand, it is easy to conceive that the central portion of an extremely thick lava flow might cool with sufficient slowness to afford a medium-grained type of texture, while a magma forced into a narrow fissure in cold rocks might be chilled so quickly as to assume a dense, compact, or even glassy one. Thus various modifications of the general rule can be easily imagined, according to particular cases, and yet this general rule, that the intrusive rocks are medium- to coarse-grained, the extrusive ones fine-grained to dense, is nevertheless true.

An important deduction, which follows from the above, is that the

coarse-grained rocks, since they have been formed in depth, can only become visible at the surface after a prolonged period of erosion, which has been sufficient to remove the cover and expose the igneous mass.

With respect to what has just been stated, the *porphyries* occupy a somewhat intermediate position. It would carry us too far to discuss in this place the most probable causes for this type of texture, but, in general, one may say the porphyritic texture is evidence of a rather rapid and variable rate of cooling and crystallization. Consequently, it is an infrequent feature in the great stocks and bathyliths, is much more common in the smaller intrusions, such as laccoliths, dikes and intrusive sheets, and is very commonly found in lava flows.

While the rate of cooling is the most important factor influencing the texture of igneous rocks, as discussed above, it is not the only one. The subject is too complicated a matter for detailed treatment in this work, but it may be mentioned that the chemical composition also has its influence; those magmas with low silica and much iron and magnesia tending to assume coarser grain than the ones composed of much silica, alumina and alkalies, under similar conditions of cooling. The reason appears to be that the former are less viscous, or more fluid, at lower temperatures than the latter, as already explained, page 201, and thus when they crystallize this mobility of the molecules permits the growth of larger crystal grains.

Also the presence of the included vapors which magmas contain, especially water vapor, increases the fluidity and promotes a coarser crystallization. This is very notably shown in certain places in intrusive masses, in cracks and fissures which have served as channels of escape for the gases, and which are now filled with large and even huge crystals of quartz, feldspar and mica. These very coarse masses are known as *pegmatites,* and from them are obtained the plates of mica which are used commercially.

In the case of a volcanic neck, the rock is apt to be comparatively coarse-textured for a small mass, because, by the constant upward passage of molten material to the surface, the rock masses surrounding the channel have become greatly heated, thus producing slow cooling in the last charge of magma which occupies the conduit and solidifies there when the volcano becomes extinct.

Classification of Igneous Rocks. — The different features by which the igneous rocks may be classified have now been explained. We have seen that they vary in the kinds and relative amounts of the mineral grains composing them, and that they also vary in texture. Both features are used to classify. Thus we may at once divide the igneous rocks into two groups on the basis of texture; one in which the mineral grains are sufficiently large to be identified by the eye alone, or aided by a pocket lens; and another in which they are too minute for this to be done. In the latter case further

subdivision has to be carried out on the basis of color and general appearance and according to this the rocks are divided into *felsites* (light or medium colored rocks) and *basalt* (black or nearly black rocks). These have been previously explained. The group in which the grains are sufficiently large for the component minerals to be recognized (usually about the texture of loaf sugar) may be termed *grained* rocks and can be subdivided on the proportions of the constituent minerals. They can be divided into two main groups, one in which feldspar is the predominant substance; and another in which it is subordinate, or lacking, and the dark iron and magnesia minerals (hornblende and pyroxene) are the chief components. Each of these may be further subdivided, in the first, as to whether the feldspar is accompanied by quartz, or not, and in the second, as to whether pyroxene or hornblende is the dominant ferromagnesian mineral. Further divisions are made as to whether the texture is even-granular or porphyritic. These various distinctions and the names of the different kinds of igneous rocks which they make are exhibited in the following table.

TABLE OF CLASSIFICATION OF IGNEOUS ROCKS

A. Grained, constituent grains recognizable. Mostly intrusive

	a. Feldspathic rocks, usually light in color		*b.* Ferromagnesian rocks, generally dark to black	
	With quartz	Without quartz	With subordinate feldspar	Without feldspar
Even-granular (nonporphyritic)	GRANITE	SYENITE	DIORITE (with hornblende) GABBRO (with pyroxene) DOLERITE (undetermined)	PERIDOTITE Pyroxenite Hornblendite
Porphyritic	GRANITE-PORPHYRY	SYENITE-PORPHYRY	DIORITE-,ETC., PORPHYRY	

B. Dense, constituent grains nearly, or wholly, unrecognizable. Intrusive and extrusive

	a. Light colored, variable; usually feldspathic	*b.* Dark colored to black; usually ferromagnesian
Nonporphyritic	FELSITE	BASALT
Porphyritic	FELSITE-PORPHYRY	BASALT-PORPHYRY

C. Rocks composed wholly, or in part, of glass, Extrusive

Nonporphyritic	OBSIDIAN, Pitchstone, Pumice, Scoria, etc.
Porphyritic	Vitrophyre (Glass-porphyry)

D. Fragmental igneous material. Extrusive

TUFF and BRECCIA (Volcanic ashes, bombs, etc.)

Remarks on the Table. — Leaving out of account the rare glassy rocks, and tuff and breccia, the following remarks may prove of service to the student in understanding the classification of igneous rocks, as shown by the table given above, especially to those who have little, or no knowledge of mineralogy.

He should notice that there are three textures employed: *grained* (relatively coarse), *dense*, and *porphyritic*. Since, ordinarily, he cannot be expected to distinguish between pyroxene and hornblende, the only distinctions which affect the mineral composition are based on *color*, light to medium, or dark to black, with one exception. The exception is the difference

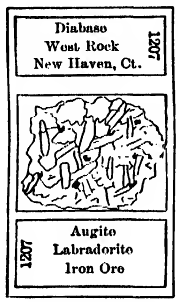


Fig. 254. — Thin section of a rock.

between quartz and feldspar, which shows whether the former is present, or not, and this is based on *cleavage*. Feldspar has good distinct cleavage, quartz has none; see Appendix A, on cleavage, feldspar, and quartz.

As a result of these differences of texture, color, and cleavage, the student will observe that the igneous rocks form six groups as follows: *granite, syenite, dolerite, peridotite, felsite* and *basalt,* and each of these, with the proper texture, is a corresponding porphyry. The first four are grained rocks, distinguished by minerals and color, the last two are dense, and are told by the color alone. Peridotite porphyry is known, but is so rare that its mention is omitted. With these points in mind the classification is simple.

Method of Study. — The classification which has just been described is based upon what can be recognized by the eye, aided, perhaps, by a pocket lens. It is thus termed a *field* classification and sometimes *megascopic* (Greek *mega,* great), in contrast to one based upon results obtained *microscopically,* by the study of thin rock slices. In the latter method a chip of rock is ground flat with emery on a metal plate, then cemented to a piece of glass and the other side ground down, first with coarse, and successively with finer and finer emery powder until the section is as thin as paper. In this way the minute mineral grains composing the densest and blackest of basalts become transparent, and may be studied and determined under the microscope. See Fig. 254. In this study polarized light is used, and a general knowledge of minerals, of their crystal characters and optical properties, is necessary. It would require too much detail to describe further this mode of studying rocks, which combined with the examination of them by chemical means, has developed into a separate geological science, called *Petrology,* the science of rocks, but it should be stated that so much additional informa-

tion is gained by these processes that the ultimate classification of igneous rocks is much more complicated than the simple scheme outlined above.

Granite. — As may be seen from the scheme of classification, this rock is composed chiefly of quartz and feldspar. It also generally contains in variable amount dark specks or flakes of mica, less commonly of hornblende, or both. It is the most important intrusive igneous rock, and appears to be one, if not the main, constituent of the basement part of the continental masses, or floor upon which the rocks of later sedimentary age were deposited. It also appears of younger age in the form of great stocks and vast bathyliths which have displaced these younger rocks. In these occurrences it is either in the form of true granite, or in a certain modification of it which we shall see later among the metamorphic rocks, and known as gneiss. Since granite is formed at some depth it is only after prolonged erosion that it appears at the surface, hence it is seen chiefly in those parts of the continents long exposed, and especially where crumpling and crushing of the shell has happened; that is to say, in mountain regions. There are many varieties of granite, based on color, texture, etc. Its common occurrence is shown in the fact that there are few states in the Union, or provinces in Canada, which do not contain exposures of granite, and its use as a building-stone, and for various purposes, is well known.

Syenite. — This is like granite in composition and texture, but differs in containing little, or no quartz. Several varieties are distinguished, based on the character of the feldspar, and the accompanying feldspar-like mineral. Thus in *syenite proper* the feldspars are alkalic, that is, contain soda and potash, but little, or no lime. In another variety, in addition to the feldspars, a feldspar-like mineral, *nephelite*, $NaAlSiO_4$, is present, and the rock is known as *nephelite-syenite*, or *foyaite*. Another rare type contains corundum, Al_2O_3. These syenites are not common rocks, nor, as a rule, do they occur in very large masses compared with granite. A variety of this class of igneous rocks, one in which the feldspar known as labradorite, composed of soda and lime, is the chief constituent, is called *anorthosite*. It is of importance, although the number of known occurrences is not many, from the large and sometimes vast masses which it forms. Areas of it are found in eastern Canada, from Labrador to Ontario, covering hundreds and even thousands of square miles; in the Adirondacks, Minnesota, Norway, etc.

Diorite, Gabbro, Dolerite. — These are usually more or less dark colored, heavy, massive rocks. The iron-magnesia silicate, in the coarser varieties, forms dark to black specks and grains which equal in number, or overbalance, the lighter colored grains of feldspar. The kinds are based on the nature of the ferromagnesian mineral; if it is hornblende the rock is *diorite*, if pyroxene it is

called *gabbro*. The distinction between the two ferromagnesian minerals, given in the Appendix, is often very difficult to make, and not infrequently impossible. In this case the term *dolerite* may be used, signifying a rock with an undetermined ferromagnesian component equal to, or in excess of, the feldspar. This class of rocks, while very abundant in intrusions, is not commonly found in the extensive bathyliths and stocks in which granite occurs. They are more often seen in smaller stocks, intrusive sheets, dikes, and sometimes forming the inner part of heavy extrusive masses. When rather fine-grained, appearing as dark heavy rocks, occurring in dikes and sheets, they are sometimes called *trap*, from a Germanic word meaning stairs, in allusion to the step-like appearance the exposed dikes often present.

There are many varieties of this class of rocks recognized by petrologists, based on the presence of particular minerals and textures. One of the most important, composed of pyroxene, labradorite feldspar, and iron-ore, with a certain textural arrangement of the minerals, is known as *diabase*. The larger part of the great trap sheets of the lower Connecticut valley and of northern New Jersey is composed of diabase.

Peridotites. — These rocks, composed generally of variable mixtures of ferromagnesian minerals, with olivine (peridote), $(Mg,Fe)_2SiO_4$, are not common, and are usually found in minor intrusions, dikes, sheets, small stocks, etc. They are very interesting and important, however, as being the source of ores of chromium, nickel, platinum, and of the diamond. They are generally very dark to black and heavy from the large amount of iron-bearing minerals present. A variety composed wholly of olivine is known as *dunite*, and in the Carolinas the occurrences of it contain the mineral corundum, Al_2O_3, which is used as an important abrasive in the manufacture of emery wheels, etc. The diamonds of South Africa occur in volcanic necks, or pipes, composed of this rock, and they have been also found in somewhat similar intrusions of it in Arkansas.

Porphyries. — As may be seen by reference to the table of classification there are various kinds of porphyry, depending on the coarseness of the ground-mass and its composition, and on the kinds of minerals which may be embedded in it as phenocrysts. Thus we may have granite-porphyry, syenite-porphyry, or felsite-porphyry. Feldspars are the most common phenocrysts, quartz is seen in many occurrences; sometimes dark to black flakes or prisms of mica, hornblende or pyroxene occur. The porphyries are a very common class of rocks, found chiefly in the minor intrusions, in dikes, sheets, and laccoliths, and often in necks; they are not often seen in the great stocks and bathyliths. They are seen also as composing many extrusive lava flows. The intrusions of porphyry in the Rocky Mountains' region are very common, and in many cases

are accompanied by valuable deposits of gold, silver, lead, and other ores, where they come in contact with limestone. Examples of this are seen at Leadville and other places in Colorado, Montana, Nevada, etc. Porphyries rarely make good building stones, as the masses are generally too much divided by joints, but in places they serve as excellent road material. A porphyry is shown in Fig. 253.

Felsite and Basalt. — Felsite represents the dense lava forms of the intrusive granites, syenites, etc. Pure felsite is not common because, generally, phenocrysts of feldspar, quartz, and mica are present, making felsite-porphyry. The number of these embedded crystals varies within the widest bounds, so that there is every transition between felsite and felsite-porphyry. The colors vary from white to gray, red, purple and brown. When the color is very dark gray, dark green, or black the rock is *basalt,* the common effusive of the ferromagnesian magmas and granular rocks, less often seen in dikes, sheets, etc. The effusive occurrences of felsites and basalts have been already treated under volcanoes and eruptions. The enormous tracts of land in western America, in India, etc., flooded by outflows of basalt have been mentioned.

The feldspathic lavas, here called felsites, are subdivided by petrographers into groups based on the nature of the feldspars and other minerals, as shown by microscopical study and chemical analysis. They are as follows:

Chief component minerals	Rock name	Equivalent coarse-grained rock in petrographic classification	Equivalent coarse rock in the classification of this book
Alkalic feldspars and quartz.	Rhyolite	Granite	Granite
Lime-soda feldspars and quartz	Dacite	Quartz-diorite	Granite
Alkalic feldspars, little or no quartz	Trachyte	Syenite	Syenite, mostly
Soda-lime feldspars, little or no quartz	Andesite	Diorite	Syenite and Diorite
Alkalic feldspars and nephelite	Phonolite	Nephelite Syenite	Nephelite-Syenite

These terms, rhyolite, andesite, etc., are constantly used by geologists on the basis of microscopical study and experience, but, usually, the distinction between the varieties cannot be accurately made without such study, and for a general term felsite is used for the group.

Glassy Rocks. — Volcanic glasses occur on the surface of outflows of lava, as thin crusts, or where a lava flow has been very quickly cooled, and they are mostly limited to felsite-magmas. Bright, clean, hard volcanic glass is called *obsidian,* and *pitchstone* when the luster is duller and more pitchy. *Pumice* is a frothy condition of the glass. The spongy, scoriaceous forms

seen on lava are apt to be more or less glassy. In past times obsidian was much used by primitive peoples in making weapons, implements, etc. The ancient Mexicans were especially skillful in fashioning knives and razors from it. Natural glasses, like the obsidian of the Yellowstone Park, are apt to contain crystallized minerals in rounded forms with radiating structures, known as spherulites, or lining shell-like cavities known as lithophysæ (stone bubbles).

CHAPTER XIII

METAMORPHISM AND METAMORPHIC ROCKS

Definition of Metamorphism. — Observation teaches us that, in addition to the igneous and sedimentary rocks previously described, there is a third class which cannot be directly referred to either, and these have been termed the metamorphic. Further study of them shows that in some places these rocks may be found to pass gradually into those whose fossils and stratification prove them undeniably of sedimentary origin, while on the other hand, in other places, the metamorphic grade into rocks whose characters show, no less conclusively, that they are of igneous origin. From this we learn that the metamorphic rocks are closely allied to both of the other classes and are, indeed, formed from them by processes it is our purpose to investigate and study. The word *metamorphic* means *changed in form,* and *metamorphism* is used as a general term for all those changes by which the original characters of rocks are more or less completely altered, in that their component kinds of minerals and textures are transformed into other minerals or textures, or both. The change may be so great that the metamorphic product bears no resemblance to the rock from which it was derived, but appears like one of a new kind. Where sedimentary rocks have been thus thoroughly *metamorphosed* they are much harder, denser, more crystalline, and the fossils and, perhaps, even the marks of stratification, have been more or less completely obliterated. As to the igneous rocks, the particular features which distinguish them may disappear, and they may assume a banded appearance and cleavage which resemble those of sedimentary kinds.

Thus limestone may pass into highly crystalline marble with consequent loss of color and disappearance of fossils; basalt may be converted into green, slaty rocks which give no hint of their original igneous nature. All stages of transition may be found between such extremes, but under metamorphic rocks we understand that the changes of the original rocks have been so profound that, as stated above, their original characters have been entirely obliterated, or nearly so, and distinctly new kinds of rocks formed. The various changes which rocks undergo from the effects of *weathering,* are, strictly speaking, to

be classed as metamorphic. But they have been already considered under the work of the atmosphere and the production of soils, therefore these agencies, and the soils and weathered rocks which result from their action, are not considered in this place.

Metamorphic Agencies. — These are mechanical movements of the earth's crust, downward pressure of superincumbent masses, horizontal thrusts, chemical action of liquids and gases, and the effect of heat. These may be simplified into the effects of movement, water solutions, and heat, and to produce complete metamorphism in rocks, probably all three of these are required, though not necessarily all to the same extent. For sometimes the effect of one factor, such as heat, may greatly predominate, that of liquids be less marked, and those of pressure or movement be quite negligible. Thus in the metamorphic changes induced in surrounding rocks by the intrusion of a body of molten magma in the form of a neck or stock, heat is, perhaps, the main agent, while pressure is of little or no effect. We will consider the different agencies in detail.

Movement and Pressure. — Simple downward pressure, sometimes called *static pressure,* as exerted in the upper part of the earth's crust by the weight of the overlying layers, appears in many places to have had little metamorphic effect on rocks. It must tend to consolidate sediments by bringing the grains together, but instances are known where strata have been buried for long geologic periods under great thicknesses of overlying beds without having suffered any notable metamorphic change, as may be observed where they have been gently raised and exposed by erosion. On the other hand, in various places, level-lying strata, which have not been folded or crushed, and have not been apparently subjected to very great vertical pressure, now appear highly metamorphosed. They are generally of great geological age. In this case we may suspect that great heat has aided the pressure in effecting the change. It is also natural to suppose that the enormous pressure which reigns at greater depths in the shell must be a powerful factor in inducing certain chemical work and effects in rock formation, but we have at present no definite information, or means of learning about them, and our ideas on the subject are mostly in the nature of speculation.

With respect to *movement* it is otherwise. The crust of the earth, as we shall see later, has been in many places, at different times, under great compressive force which has found relief by wrinkling up the outer shell into mountain ranges. By this mountain-forming force whole masses of strata, often with included

igneous rocks, intrusive and extrusive, are folded, crushed, and mashed together in the most involved and intricate manner. Not only are they subjected to vast pressure, but also, in the mashing, to enormous shearing stresses, which produce forced differential movements among the rock particles. The *shear* may be characterized as a sliding of the particles upon themselves, so that a slipping of adjacent layers, relative to one another, is produced, while *mashing* is a process of flowage by which adjacent layers become thinner, but do not slide one upon another. It is particularly this mashing and shearing which are of great power in producing metamorphism. The visible effects may often be seen by the manner in which large crystals, included pebbles, or fossils, are flattened and elongated, in the plane at right angles to the mashing force. It is possible, in fact, for mashing and shearing alone to produce rocks having the characteristic outward metamorphic texture, without change in the original mineral composition, but in combination with heat and water, this is of the highest importance in inducing chemical changes, and the production of new minerals. It is, indeed, noticeable that as long as rocks retain their original position, they may be unaltered, but as we commence to find them disturbed by compressive mountain-making forces, they begin to show signs of metamorphism, and largely in proportion to the degree to which they have been folded up, mashed, and sheared, they become more and more metamorphosed. The effects produced in this way are commonly referred to as *dynamic metamorphism*, or *dynamo-metamorphism*. It should be understood, however, that, in the use of this term, not pressure alone, but the action of solutions and heat is also included.

Heat. — The effect of heat as a metamorphic agent is very strong, as is well seen where intrusive igneous rocks have come in contact with sedimentary ones and metamorphosed them. It increases greatly the solvent action of solutions; it tends to break up the chemical compounds of many minerals, and to thus make new combinations. The heat needed for metamorphism may possibly in part be that of the interior of the earth, it may be supplied in part by the transformation of energy resulting from the movements, the folding and crushing of the rock masses, but it is probably mostly due to the intrusion of molten magma, which is apt to rise and be intruded into rock masses when they are uplifted and folded.

Liquids and Gases. — The most important of these is water, which, with heat and pressure, becomes a powerful chemical agent. It acts as a solvent, and helps crystallization, and in the making of

new chemical compounds. It is aided in its action by material it may carry in solution, such as alkalies, and by volatile substances coming from the magma intrusions, such as various acid-forming substances, fluorine, for example, as already explained under volcanic action. This explains the presence in metamorphic rocks of minerals, which contain chemically combined the elements of water and other gases, and, as we shall see later, the veins and ore deposits frequently found in them.

Effect of Depth. — The outer shell of the earth may be divided into different zones, according to the various geological activities

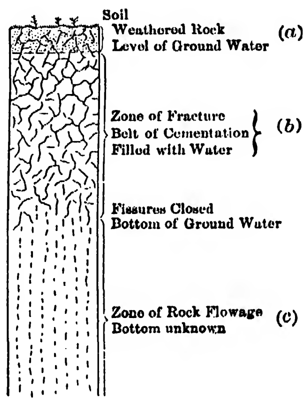


Fig. 255. — Diagram to illustrate different zones in the earth's outer shell.

going on at different levels. They are illustrated in the diagram shown in Fig. 255. Below the upper layer of soil the bed-rock is full of fractures, and, as far down as the surface of ground water, it is exposed to atmospheric agencies, the moisture, carbonic acid, etc., which tend to cause decay and convert the rocks into soil. It is a zone of rock destruction, as shown in the first chapter, and may be called the *belt of weathering*, (*a*), Fig. 255.

Below this belt comes the zone (*b*) in which the rocks are full of cavities and fractures filled with water. The upper limit is that of the surface of ground water, the lower that where openings cease, as described in the next zone. It may be called the *zone of fracture*, if we disregard the upper limit. In this the action of water is most important, it performs chemical work, aided by the carbonic and other acids it may carry. The tendency is for the silicate minerals of the rocks to change into those containing water in combination, or into carbonates. Substances are taken into solution, and, added to by those leached downward from the belt

of weathering, are deposited in the fissures and pores of the rocks. From this cementing and filling of cavities the zone may be termed the *belt of cementation.*

Below this comes the zone (*c*), Fig. 255, where the pressure of the superincumbent masses is greater than the elastic limit of the strength of rocks; they crush under it, and are to be regarded as being in a relatively plastic condition. As a result, all openings and fractures are closed, and this must mark the limit downward of the percolation of ground water. The upper limit of this zone is variable and depends on geological conditions; in times of quiet it may be 15 miles below the surface; in times of compression and mountain-making it may be at a much lesser depth. Where its lower level may be we do not know. In this zone the enormous pressure and increasing heat of the earth are the chief agencies; liquids and gases are less important and tend to be squeezed out; thus carbonates change to silicates and CO_2 is expelled. The new mineral compounds must tend to be of smaller volume and higher specific gravity from condensation. This zone of rock flowage we may term the *zone of constructive metamorphism.*

It is chiefly in the lower part of the belt of cementation, or zone of fracture, and in the upper part of the zone of rock flowage that the work of producing metamorphic rocks, as we know them, is done.

The zone of rock fracture has been called the zone of *katamorphism,* and that of rock flowage the zone of *anamorphism,* by Van Hise; the meaning of these terms is that one is a downward change, or breaking up into simpler compounds, while the latter is an upward change or reconstruction into more complex compounds, or minerals. These terms are frequently used by geologists in referring to metamorphism and metamorphic rocks.

Regional and Local Metamorphism. — It should be stated before proceeding further that for practical purposes two varieties or effects of metamorphism are recognized by geologists. In the first the rocks are changed or metamorphosed over extensive regions; all the different factors of metamorphism have worked upon them; but pressure, with mashing and shearing, has been especially important, and as a result the rocks are apt to have a peculiar texture which distinguishes them, and which will be presently described. In recognition of the wide extent to which rocks may thus be changed this has been called *regional metamorphism,* and sometimes general metamorphism, and the dynamic metamorphism referred to previously is merely a pronounced phase of it in one direction.

But, on the other hand, rocks, especially sedimentary ones, may

be metamorphosed by the heat, liquids, and gases issuing from intrusive molten magmas which may come in contact with them. Here it is evident that mashing and shearing are unimportant; the rocks are wanting in the characteristic texture mentioned above and described beyond, but may yet be thoroughly changed; thus chalk may be altered to marble. With reference to the fact that metamorphism produced in this manner is confined to the immediate neighborhood of the igneous rocks which have produced it and, therefore, compared with regional metamorphism, is limited in extent, it is known as *local,* or very commonly *contact metamorphism.* We will go on with the consideration of regional metamorphism, and local, or contact metamorphism will be treated at the end of this chapter.

Minerals of Metamorphic Rocks. — The chemical compounds, which form the minerals found in the rocks, vary greatly in their ability to withstand the changes of conditions which different geological processes subject them to. With new chemical and physical factors operating upon them, they will tend to change into new minerals, or those chemical combinations which will be the most stable under the new conditions. Thus we see feldspar alter into clay and other substances through the action of water and carbon dioxide, as explained under soils, page 25. The igneous rocks are characterized by one set of minerals, chiefly silicates, while carbonates and hydrated oxides and silicates are mostly found in the sedimentary rocks. Some minerals like quartz have a wide range of stability and are found in all three classes of rocks, but many minerals when subjected to metamorphic processes are converted into other minerals; thus carbonates are apt to be changed into silicates. Quartz, the feldspars, mica and hornblende are found in both igneous and metamorphic rocks, while common garnet, staurolite, cyanite, talc, chlorite, and serpentine are common minerals of metamorphic varieties.

Texture. — Most metamorphic rocks resemble the igneous in that they are highly crystalline, but they differ from them in possessing a parallel structure which may at times closely resemble stratification. This parallel structure expresses itself to a variable extent by a foliated, laminated, or as it is often termed, a *schistose* texture, and a rock possessing it is known as a *schist.* By reason of it a rock tends to split, or cleave, more or less perfectly in the direction of a plane passing through it, which we may call the plane of cleavage. Although it is the characteristic texture of metamorphic rocks, which for this reason have been sometimes called the *crystalline schists,* there are a few, such as serpentine, marble and quartzite, which may not show any trace of this parallel schistose structure and cleavage. In some cases the parallel structure is straight, or nearly so, as seen in Fig. 256, for considerable distances; often, how-

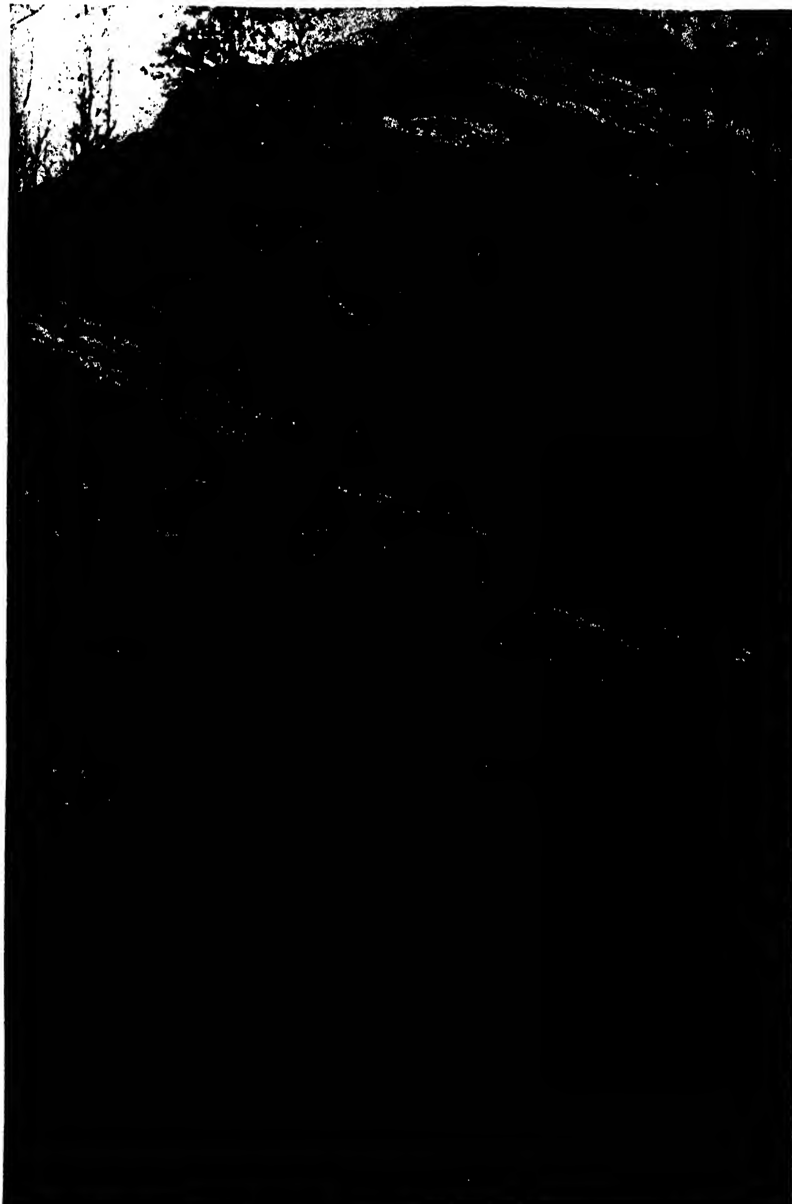


Fig. 256. — Banded gneiss, Portland Township, Ottawa Co., Quebec. M. E. Wilson; Geol. Surv. of Canada.

ever, the banding is very much contorted, bent, or curled, showing the kind of mashing and kneading the original rocks were subjected to. See Fig. 259.

Observation shows that the schistose texture is due to the arrangement of unlike mineral grains in layers or flattened lenses, or to parallel grouping of prismatic or tabular minerals, such as hornblende or mica, or to a combination of both. It is a result of the granulation and recrystallization to which the original rocks were subjected, and has been imposed upon igneous and sedimentary rocks alike. The resemblance of the banded, laminated appearance of schistose metamorphic rocks to stratification led in the past to the erroneous view that they were wholly derived from stratified ones; that they could also be made from igneous rocks was learned much later.

Cleavage. — The cleavage which is exhibited by schistose metamorphic rocks is most perfectly developed in slates, so much so that this variety of it is often spoken of as *slaty cleavage*. Slates used for roofing, blackboards, and other purposes are examples of this. Its origin has been the cause of much speculation and the subject of investigation, along both experimental and mathematical, as well as geological, lines. From this it has become clear that it is the result of great pressure upon the material, and that *the planes of cleavage are at right angles to the direction of pressure.* When fine-grained sediments, muds and clays, are subjected to intense pressure, oblong particles tend to rotate so that their lengths are perpendicular to the direction of pressure; they also tend to become flattened perpendicularly to it. More important is the fact that many of the elongate or flattened minerals, such as mica, kaolin, chlorite, and hornblende, have an excellent cleavage parallel to the long or flat directions. All these features tend to give the rock a capacity to cleave readily in one direction. Slaty cleavage is thus partly molecular, when it passes through a single mineral particle, and partly mechanical, when it passes between arranged or unlike particles. A considerable part of the minerals may not be original, such as the micas, but formed by the metamorphism accompanying the pressure.

The cleavage planes do not necessarily bear any definite relation to those of original bedding. The beds were laid down in horizontal position and the direction of pressure is also horizontal or nearly so; the cleavage planes, being at right angles to this, may cut the bedding at right, or highly inclined angles. But as the beds may be folded before the pressure becomes intense, the cleavages may pass through the bedding at various angles, though they themselves are strictly parallel, see Fig. 257, Fig. 258, and also Fig. 260.

Although by far the greater number of slates have been made from original fine sediments, muds and clays, slaty rocks have also been produced by the mashing of fine-grained igneous rocks, such as felsites and basalts, and beds of

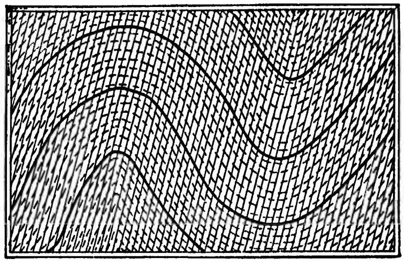


Fig. 257. — Slaty cleavage in folded beds.

volcanic ash. In this process original characteristic features in the rocks may become greatly distorted and even obliterated; thus fossils and pebbles in the stratified rocks and embedded crystals and other structures of the igneous may be flattened into lenses or squeezed out into cylinders. And it must also be

Fig. 258. — Slaty cleavage cutting at a high angle beds folded in a syncline. Slatington, Pa. E. B. Hardin, U. S. Geol. Surv.

remembered that what has been here said of cleavage in slates is equally true of other schistose rocks in which it differs only in degree of becoming less perfectly developed.

At times cleavage may be mistaken for original bedding, unless care is taken, and wrong interpretations of geological structure obtained. It is sometimes important to indicate it on geologic maps and this may be done by observing its dip and strike, like that of a bedding plane. The important relation it bears to mountain ranges and their origin will be discussed under that subject.

Places of Occurrence. — Metamorphic rocks are widely distributed over the earth's surface, and in some regions they are the only kinds exposed over extensive areas. This is true in eastern Canada, where, in places, considerable bodies of intrusive igneous rocks are associated with them. They are found quite generally in New England, in the Adirondacks and in a strip of country running from northern New Jersey to Georgia. Other occurrences will be mentioned in the second part of this work. There is reason also for thinking that over the continental areas they must form the basement upon which all the later unmetamorphosed stratified rocks rest. For wherever these latter are sufficiently cut away by erosion this metamorphic basement appears, except where it has been cut into by intrusion of stocks and bathyliths of granite and other igneous rocks. The metamorphic rocks also form the interior core of many mountain ranges, and have been exposed by erosion. These mountain ranges, as will be discussed later, have been made by folding of the strata, and in proportion to the intricacy of the folding and mashing, so is the degree of metamorphism of the rocks increased.

The relation between folding, elevation, and metamorphism is so well established that, where we find rocks intricately folded and very metamorphic, we assume that an elevation once existed but has been eroded away, or, in general, that metamorphic rocks can only be exposed at the surface after continued erosion. Following out this idea, metamorphic rocks are sometimes spoken of as *continental* rocks, because they imply (when originally of stratified kinds) continued erosion of land masses; laying down of beds of sediments, and folding and crushing of the latter to give metamorphism, with incidental production of mountain ranges; and lastly erosion again to expose the metamorphic rocks. Such an array of processes could occur only on a great scale and therefore on and about continental masses; consequently when metamorphic rocks are found in place on Fiji, New Caledonia, South Georgia and other islands, it is held that this proves that these are really exposed portions of fragmented continental masses. See page 117.

Age of Metamorphic Rocks. — Some of these facts, previously mentioned, led to the view that, from the geological standpoint, metamorphic rocks must be very old. This by no means necessarily follows, nor is it always true. For while we find almost unmodified beds of quite early geologic age in Russia and in the upper Mississippi valley, which have been changed but little from their original horizontal position, on the other hand, strata of a comparatively recent period which have been greatly folded up in the Alps, the Coast Range and in some other mountains have been strongly metamorphosed. It merely depends on whether they have been subjected

to metamorphic processes or not, and the older the rocks are, the more likely they are to have suffered from them. Time, however, is one of the most important factors in metamorphism, and, even where relatively recent strata have been changed and then exposed, the time involved, from our standpoint, is immensely long.

Kinds of Metamorphic Rocks

Introductory. — Since the metamorphic rocks are made from both the stratified and the igneous, and there are almost infinite varieties of both of these, it follows that there must be a very great number of different kinds of metamorphic products. Yet in the same way that we were able for ordinary purposes to gather the igneous and stratified rocks into a small number of groups, so we can consider the metamorphic under the few most important types.

The sedimentary strata are very largely made of disintegrated igneous rocks. In the process of breaking down and disintegration it may happen that there is not much weathering and chemical change. In this case the sedimentary deposit will not differ very greatly from the original igneous rock in chemical and mineral composition. Thus the red-brown sandstone (arkose) of the Connecticut valley, which is full of feldspar, has practically the same composition as the masses of granite of the adjacent region. If such arkoses are so thoroughly metamorphosed as to lose their original characters, it is evident that we could not distinguish them from the metamorphosed granites, or determine what their former status was. From this it will be clear that, while in some cases we can tell the origin of a metamorphic rock at once, as in marble and quartzite, and in others after careful study in the field and laboratory, in many cases we are unable to ascertain from what they were derived.

Classification. — Remembering the simple classification of the sedimentary rocks previously given, it is possible, in a general way, to show the relation between the most common and their metamorphic derivatives in the following table:

Sediments	Compacted strata	Metamorphic rocks
Gravel	Conglomerate	Gneiss, and various schists
Sand	Sandstone	Quartzite, and various schists
Silt and clay	Shale	Slate, and various schists
Lime deposits	Limestone	Marble, and various schists

In the case of the igneous rocks, recalling that they may be roughly divided into two main groups, the one chiefly composed of light-colored feldspathic minerals, and the other mostly of dark ferro-magnesian ones, we can illustrate also, in a very rough and general way, the relation between them and their metamorphic derivatives in the following table:

Igneous rocks	Metamorphic rocks
Coarse-grained feldspathic types, such as *granites*, etc.	*Gneiss*
Fine-grained feldspathic types, such as *felsite*, *tuffs*, etc.	*Slate* and *Schists*
Ferromagnesian rocks, such as *dolerites* and *basalt*	*Hornblende-schists*, various schists, and *serpentine*

Comparison of the tables will show that gneisses and schists may have diverse origins, as previously pointed out. Combining the results of these tables, we may obtain the following main groups of metamorphic rocks, distinguished according to their mineral composition or by their texture, or by a combination of both.

Grouping of Metamorphic Rocks

1. *Gneisses,* rocks containing feldspar.
2. *Mica-schist* and *quartzite.*
3. *Slates* and phyllites.
4. *Hornblende-schist;* talc-, and chlorite-schists.
5. *Marble,* dolomite, mixed carbonate-silicate rocks.
6. Serpentine. Iron-ores.

Gneiss. — The common varieties of this rock (pronounced nice) consist, like granite, of quartz, feldspar, and mica, but in gneiss the mica is arranged in more or less definite planes and the rock has thus a rude cleavage. Sometimes hornblende may accompany or replace the mica, and other minerals, such as garnet, may also occur, giving different varieties. They are variable in color from light to dark, and are fine to coarse in grain. All degrees of transition between granite and gneiss are very common, and in other cases, where gneisses were made from conglomerates, the original pebbles may still show as lenticular masses. Gneiss is one of the most common of metamorphic rocks, and it appears also as, perhaps, the most deeply situated of any known rock, formed, probably, in the deepest

zones of metamorphism. Some rocks are spoken of as granite-gneisses, and it seems probable that in some cases the gneissoid texture has been assumed, through mashing and shearing, by magmas while still in a pasty, viscous condition. A view of beds of gneiss is seen in Fig. 259.

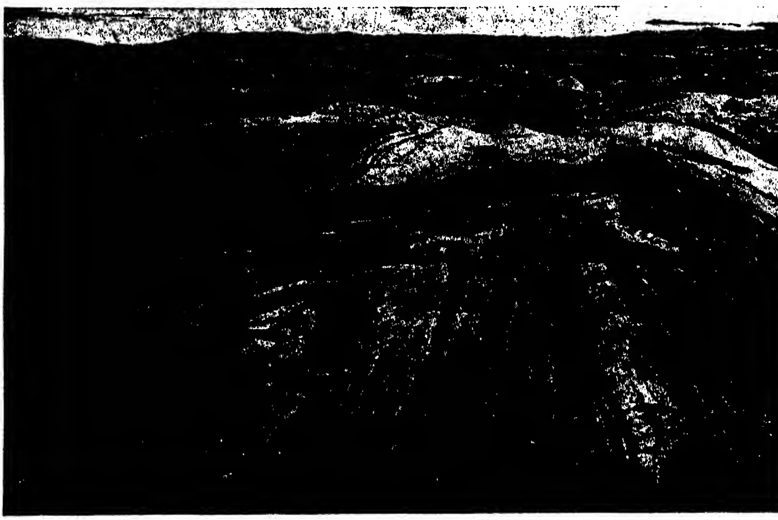


Fig. 259. — Contorted gneiss; Fullerton, Hudson Bay, Canada. A. P. Low. Geol. Surv. of Canada.

Mica-schists and Quartzite. — When a sandstone becomes so firmly cemented by deposit of silica that the fracture takes place through the grains of quartz sand, instead of around them, it has become a *quartzite*. In this condition it shows no schistose structure, but is massive. If subjected to mashing, a quartz schist may be formed, or, if it is impure sandstone, mica is liable to develop and may increase in amount until it appears the most prominent ingredient, and the rock becomes *mica-schist*. All degrees of transition between gneisses, quartzites, and mica-schists may be found, depending on the relative quantities of quartz, feldspar, and mica. Quartzites are usually massive rocks of light colors, white, gray, reddish, or buff, and of hard flinty aspect. Mica-schist is a very schistose, often friable rock, usually of a silvery luster, and often dotted with common red garnets.

Slates. — The origin of these rocks from fine-grained sediments such as muds, clays and ash deposits by the action of compressive forces has been already discussed. While they may have various

colors, red, green, gray, etc., the most common one is dark gray to black, due to carbonaceous material from organic matter in the original muds. As is well known, they are quarried for roofing slates, blackboards, and other purposes. See Fig. 260. They are closely related to shales, but the distinction between them is that such cleavage or lamination as a shale may possess is due to original bedding planes; whereas in slates it is a secondary induced phenomenon, which, as previously stated, may bear no relation to bedding. Slate is sometimes called *argillite* in reference to its origin from clay (Greek argillos, clay).

Fig. 260. — Illustrates the occurrence of slates and cleavage. Slate quarries. Brownsville, Me. T. N. Dale, U. S. Geol. Surv.

Phyllites. — These are rocks resembling slates, but having a larger proportion of mica, which gives them a silky, glimmering luster. They are transitional between slate and mica-schist. The name, which means "leaf stone," has been given for the remarkable cleavage, or fissile character, of these rocks. They appear in some cases to have been formed, like the ordinary slates, from sediments, but to be more highly metamorphic and recrystallized. In other instances they have been made from igneous material, felsite lavas, tuffs, etc., by mashing, shearing and accompanying agencies of metamorphism. They have sometimes been called "hydro-mica-schist" in America.

Schists: Hornblende-schist. — There is a great variety of rocks, depending on different minerals which compose them, which have a more or less pronounced foliated, or schistose, structure.

Schist, as previously mentioned, is a general name for the group, and *hornblende-schist* may be taken as a most common and typical representative. The rock is generally dark green to black, and the parallel prisms of hornblende, if not too large, usually give it a silky luster. The rock-cleavage is almost slaty in some cases. Talc-schist and chlorite-schist are other common varieties, in which talc and chlorite are predominant minerals.

Marble. — This is the metamorphic condition of the sedimentary rocks formed by lime deposits, such as limestone and chalk. Generally, the marks of bedding, fossils, etc., are effaced and the material converted into crystalline grains of calcite. It is, therefore, harder, more compact, with purer colors, and takes a good polish. Just as there are ordinary limestones consisting only of carbonate of lime, and dolomitic limestones containing magnesium carbonate, $MgCO_3$, in variable quantity in addition to the $CaCO_3$, so we have *lime* marbles and *dolomite* marbles. Commercially, as marble is used, this chemical difference is not a matter of importance, but geologically, it is of interest because the kinds of minerals that are liable to be associated with the marbles, or to be found, in some cases, scattered more or less thickly through them, are quite different in the two kinds. Marble is generally massive and shows no cleavage, even when found in regions where its association with schists shows it must have been subjected to enormous mashing and shearing stresses. The reason for this appears to be that the mineral calcite has a curious property of being able to permit of motion of its molecules in certain directions without the crystals being destroyed. It is analogous to what was described of ice, page 132. Owing to this the stresses are absorbed molecularly, and no arrangements of the grains are produced which show as foliation in the outward structure, as they do in schists.

Pure marble is white, the mottling, banding and colors shown by ornamental varieties being due to impurities, the red and yellow tones to oxides of iron, the grays and blacks to varying proportions of organic matter. Besides being produced by regional, marble is also formed by contact metamorphism.

Serpentine. — This name is given to a mineral, a hydrous silicate of magnesia, $H_4Mg_3Si_2O_9$, and also to a rock largely or entirely composed of it. The rock is usually greenish to black, soft, of a greasy feel, and massive, or without cleavage. Some of the blotched, lighter green varieties are used as building and ornamental stones. Most serpentines appear to have been made by hydrothermal metamorphism (action of hot waters) on deeply buried masses of igneous rock rich in magnesia, such as peridotite for example, whereby the magnesium silicates change to this hydrated variety. Impure dolomite marbles may contain magnesium silicates, olivine, pyroxene, etc., which may

alter to serpentine. 'Verde antique' appears in some cases to be a mixture of marble and serpentine of this nature.

Iron-Ore. — The mode in which beds of iron-ore may be accumulated in the stratified rocks has been already described. Such iron-ores may be subjected to metamorphic processes like other rocks and as a result the loose earthy materials may be changed to hard crystalline rocks; thus beds of limonite and clay-ironstone may be altered to hematite and magnetite.

Anthracite, or hard coal, is regarded by many as the metamorphic equivalent of bituminous, or soft coal. The degree of metamorphism is, however, very slight; were coal changed in proportion as the other metamorphic rocks we have described, it would be converted, not into anthracite, but into graphite, which is not combustible in the air under ordinary conditions.

Local, or Contact, Metamorphism

Introductory. — As previously explained, this term is used to denote the changes which are induced in already existent rocks by the intrusion into them of a mass of molten magma, and also the effect of the contact on the igneous rock which the magma itself forms in cooling. We may thus observe it from two standpoints; that of the result on the igneous rock-body, termed the *endomorphic* effect, and that of the action on the enclosing rocks, or the *exomorphic* one. Unlike their importance in regional metamorphism, mashing and crushing are generally negligible factors, and heat and the action of vapors and liquids are the chief agents in producing the changes observed. Therefore, in the changed rock, while new minerals may be formed, and it may have a harder, denser, more crystalline texture than the normal rock of the region, it very rarely shows the schistose, or cleavable structure as a result. The new rocks are massive, and not schists, except as they may retain this structure from their previous condition.

Endomorphic Effect. — In the igneous rock-body itself two effects may be noticed as one approaches the contact. The first and most usual is a change in the *texture* of the intruding rock. It grows much *finer in grain* and at the contact wall may be very dense; thus a granite may change to a felsite. The reason for this is the quicker crystallization and solidification induced in the magma by the chill of the cold rock-wall with which it comes in contact, as explained under igneous rocks, page 325. Sometimes the igneous rock is not only denser, but changes from an evenly granular to a *porphyritic texture* at the contact; which is also indicative of more rapid cooling. Sometimes no change of grain is visible, and, in this case, we must assume that the rock-wall was thoroughly heated by the flow of magma past it, as in a volcanic conduit for

example, before the final charge of magma came to rest against it. In such circumstances, the magma would not be quickly chilled, and no special change in grain might be expected. But in this case the exomorphic effects are usually much more marked.

The other effect is that sometimes new minerals, other than the normal ones of the igneous rock, may be found occurring at, or near, the contact. Thus, for example, tourmaline may be seen not infrequently in masses of granite. The origin of such minerals is due to the chemical effect of the vapors and gases of the magma, which tend to be excluded as the mass cools and crystallizes, and to escape to the margin, and into the surrounding rocks.

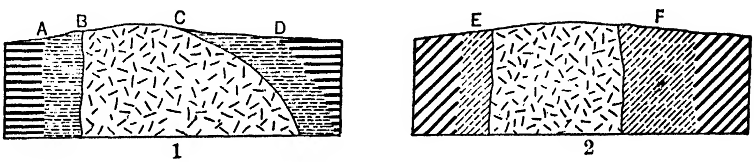


Fig. 261. — Sections of intruded stocks and their contact zones. In 1, the breadth on the surface *CD* is greater than *AB*, depending on shape of igneous mass. In 2, the width *F* is greater than in *E*, depending on inclination of beds.

Exomorphic Effects. — The most noticeable evidence of the exterior effect of contact metamorphism is a baking, hardening, or toughening of the surrounding rocks in a zone surrounding the igneous mass. As a result, it not infrequently happens that the altered rocks resist erosion better than the intruded igneous body, or the unchanged country rocks, and form projecting topographic forms, such as ridges, peaks, etc. In the case of dikes, it may happen that both the dikes, and the sedimentary beds penetrated by them, are lowered more rapidly by erosion than the hardened contact rock on either side, leaving it standing up in parallel walls. In most cases, however, the resistance to erosion is very similar to that of the igneous rocks.

The breadth of the zone depends largely on the size of the igneous intrusion; the widest and most pronounced being found about the great stocks and bathyliths. Around them it has been observed in many places that the contact zone may reach a breadth of a mile, or even more; usually it is some hundreds of yards and, with a small intrusion such as a dike, it may be only a few feet. With extrusive lava flows a small amount of baking of the soils or rocks on which they rest is often noticed.

Relation to Rock Structure. — Around an intrusion it is frequently observed that the width of the contact zone is variable;

this may depend very much on the position of the rocks. Thus in Fig. 261, section 1, the sloping inclination of the contact wall produces a wide zone at *CD*, compared with that of the vertical wall at *AB*. And in section 2 the beds at *F*, sloping into the igneous rock, tend to have their bedding planes opened, and to furnish an easy entrance to the vapors and solutions from the cooling magma. Since these vapors and solutions are the chief agents in carrying the heat and producing the metamorphism, it is clear that a broad zone *F* will be made on this side, compared with *E*, where reverse conditions are present and a narrower zone must be formed.

Results on the Different Kinds of Rocks. — The extent to which local, or contact, metamorphism produces its effects upon already existent rocks depends very much, in addition to what has been said above, upon the kinds of rocks. It should not be forgotten in this connection that intrusions of igneous rock, such as dikes, may take place into older igneous rocks, as well as into sedimentary strata. The latter, as a rule, are much more profoundly affected than the igneous rocks. For our purpose here the sediments may be divided into the three groups, the *sandstones*, the *shales* (and clays), and the *lime* rocks. On pure sandstones the effect is rather small, though near the contact they may be changed into quartzite. The lime rocks are changed into marble, of greater or less purity, the masses of which may extend for considerable distances. In the case of clays and shale beds the most notable and, generally, far-reaching results are seen, the soft shales being greatly hardened and, finally, at the contact, converted into dense crystalline rock known as *hornfels*, which in its outward appearance may strongly resemble an igneous rock, such as basalt. The igneous rocks, being the products of fusion, are generally but little affected by later intrusions, especially feldspathic kinds like granite.

In approaching a contact zone in shales, after a slight hardening, one of the most noticeable effects is the production of spots, or knots, in the rock. These may consist of small points, or lumps, or the production of prisms of some mineral, such as andalusite (Al_2SiO_5), which may be black from included carbonaceous matter. Still nearer to the contact, and at it, the knots disappear and the rock has a granular crystalline appearance, which recalls that seen in the igneous rocks.

The most interesting results are produced in limestones, especially impure, cherty varieties. Not only are they turned into marble, but a great variety of new minerals may be formed in them, depending on reactions between the bases and acidic oxides present, especially lime and silica. Thus the silica tends to drive out carbon dioxide,

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$$

and calcite is changed into lime silicate (wollastonite). If the limestone is dolomite, then magnesia takes part,

$$(CaMg)CO_3 + SiO_2 = (CaMg)SiO_3 + CO_2$$

and calcite is changed into pyroxene, and carbon dioxide liberated. Clay may be present, furnishing alumina, and iron oxides may also occur; while, in addition to the water vapor, sulphur, fluorine, boron and other acid-forming elements from the magma, may take part, and thus by various combinations, numbers of new chemical compounds, or minerals, are formed. These more complex reactions may be illustrated by the following example:

$$\begin{array}{lllllll} \text{Calcite} & + \text{ Clay} & + \text{ Quartz} & = \text{Garnet} & + \text{ Carb. dioxide} & + \text{ Water.} \\ 3\,CaCO_3 & + \; H_4Al_2Si_2O_9 & + \; SiO_2 & = Ca_3Al_2Si_3O_{12} & + \; 3CO_2 & + \; 2H_2O. \end{array}$$

Thus a limestone, impure with clay and sand, may be changed into garnet with evolution of carbon dioxide and water.

It seems quite certain that, in addition to the water and other volatile substances, silica is carried in solution into the enclosing rocks; taking part in the chemical reactions mentioned above, cementing them by deposit in their pores, as when sandstone is converted into quartzite, and forming veins of quartz in crevices and fissures. The alkalies, soda and potash, are also carried by these solutions, or emanations, from the magmas into the surrounding rocks, and by many geologists it is claimed that alumina, iron, magnesia and many other elements are thus transferred in contact metamorphism. It seems certain that in many cases this is true, but as yet the necessary chemical knowledge, which would permit us to understand exactly what takes place, has not been obtained. The importance of these assumptions we shall see when ore deposits are studied.

CHAPTER XIV

THE FRACTURES AND FAULTING OF ROCKS

Fractures; Joints

General Remarks. — The fact that in the outer shell of the earth the rocks are traversed in all directions by fractures, varying from minute crevices to important fissures, has been already alluded to in many parts of this book. We have seen their importance in the weathering of rocks and formation of soil; in the holding and in the circulation of underground water; in earthquakes, and in some metamorphic processes, and we shall meet them again in considering mineral veins. They are, indeed, of great geologic importance, both on account of the processes which give rise to them and from the results which are achieved by their aid. It is fitting, then, that we should study them in some detail.

Fractures are found in all classes of rocks, and for purposes of study they may be divided into *joints* and *rifts;* the difference between them is one of degree, the joints being developed in a single rock-mass or a certain set of strata, while the greater rifts may traverse many adjoining rock masses and extend to great distances. The joints show little or no dislocation of their contiguous walls; with the rifts there may or may not have been displacement, but at the surface their existence is generally revealed to us by differential movements on the opposite sides, as explained later under faults. We will consider the joints first.

Our knowledge of the fractures in rocks, gained by a study of surface conditions, has been greatly extended below by mining operations. Mining geologists commonly divide the fractures into the lesser or *joints,* as defined above, and *fissures,* for the greater. The latter may extend considerable distances, even a number of miles. The word *rift,* used above in a general way, includes such fissures, and also the much greater fractures which divide the outer shell into vast blocks, and are illustrated by the great San Andreas Rift of California, mentioned on page 245, or in the great Rift Valley of Africa, see page 241. It would be perhaps well to use rifts for such vast fractures, and fissures for the more common lesser ones of the mining geologists.

As ordinarily used, the words fracture, fissure, etc., imply that to some extent the surfaces of rupture are not in absolute contact, that some opening

exists between them. As employed by geologists this may, or may not, be implied. Joints are generally tightly closed; they may gape at the surface an inch or more; below, such separations are generally filled with mineral matter. Rifts and fissures usually show some separation, in most cases filled or healed by deposited material; when this is wanting and the walls are in contact, it is known as a "tight fissure" or fracture. Fissures, whether separated and filled, or tight, may exist without displacement, as seen in the mines at Cobalt, Ontario, or they may exhibit the faulting described beyond.

Fig. 262. — View illustrating joints in limestone beds. Drummond Island, Mich. I. C. Russell, U. S. Geol. Surv.

Joints in Stratified Rocks. — The smaller fractures which divide the rock masses are those which we may call joints. Examination generally shows that they are present in systems; that is, they run as divisional planes through the strata more or less perfectly parallel to definite directions. Often it happens that these directions of jointing are two, vertical, or nearly so, and approximately at right angles, and this, combined with the natural divisional bedding planes, divides the strata into series of closely fitted blocks. Or there may be three or more systems of jointing. The finer the grain of the rock, as a rule, the more perfect the jointing. Thus, in shale beds and in limestones, it may be very perfect, as illustrated in Fig. 262. Such jointing may arise through various agencies, such as the tension produced in the beds of sediments by the contraction which ensues when they are elevated from the sea-bottom to form land surfaces, and undergo a drying-out process. Or, at such times, or later, the beds may be subjected to folding, warping and torsional

effects through crustal movements, by which the joints are made by cracking in regular systems. It has also been suggested that the passage of earthquake waves through the rocks, with the sudden alternate compression and tension, is the cause of much of the minor jointing observed. The exact cause of most of the joints is not known, but they have sometimes been classified as tensional or compressional joints, according to the supposed nature of the force producing them.

Joints are a matter of great importance in all quarrying, tunneling, and mining operations where rock-work enters as an important factor, since the jointing obviously greatly facilitates progress. Otherwise, every rock fragment would have to be broken or blasted loose from bed-rock.

In regions where the stratified rocks have been definitely folded, the joints are sometimes the result of *tension* in the anticlines, and sometimes of *compression* in the folding. Slaty cleavage is thus commonly found to be associated with joints. In folded strata, when parallel with the strike of the beds, or nearly so, they are called *strike-joints;* when at right angles to this, or nearly so, they are called *dip-joints,* being in line with the dip.

It is often noticed that joints of a certain system in disturbed strata, which are probably to be associated with the folding, extend for long distances, through a whole series of beds, and are known as *master-joints.* They are contrasted with the minor joints which may be limited to a single stratum.

Joints in Igneous Rocks. — The jointing observed in igneous rocks is mostly due to the contraction resulting from the cooling of the heated mass. It occurs just after the solidification from the molten state, when the loss of heat from the newly formed solid is greatest. It may manifest itself in one of several ways, depending on the rate of cooling, the size and shape of the igneous body, and other things. Thus intrusive masses of granite and other rocks are cut by jointing planes in various directions which divide them into large blocks, often roughly tabular, or into prisms. In some cases, especially in the finer-grained felsites and porphyries, the jointing in sheets, laccoliths and dikes is on a very small scale, well shown in the talus coming from exposures of the igneous rock, which consists of small angular fragments. Sometimes in laccoliths, and similar dome-shaped intrusions, there is a shelly jointing on a large scale, parallel to the domed surface. This appears to have been caused by the planes of cooling (and parting) having descended evenly into the mass from the domed surface.

A much rarer kind of jointing seen in igneous rocks is one in which the contraction took place very regularly around certain centers, producing spherical masses by the cracking. This kind of structure is especially brought out by the weathering of the rock mass. It occurs both in intrusive bodies and in

lava flows. Igneous rock masses may also exhibit jointing, due, as in other kinds of rocks, to tensional and compressive stresses in the earth's crust. But, as they are previously jointed by contractional cooling, as explained above, this is of minor importance, since the stresses are more likely to relieve themselves by movement along the existent joints than by forming new ones.

Columnar Structure. — The most striking method of jointing in an igneous rock, by contraction on cooling, is shown when columnar structure is developed. This takes place, in general, when the extension of the mass is great in two directions and much less in a

Fig. 263. — "Devil's Post-pile"; columnar jointing in lava. Head of the San Joaquin River, Cal. H. W. Turner, U. S. Geol. Surv.

third, as in a dike, an intrusive sheet, or a lava flow. The rock-body may then be composed of a series of closely fitted prisms, which are again divided by cross joints. The prisms may have a variable number of sides, but most commonly they are hexagonal, and sometimes of wonderful regularity of form. They may be several inches, or a number of feet, in diameter, and from one foot to 200, or even more, in length. See Fig. 263. The Giant's Causeway on the north coast of Ireland is one of the most celebrated examples of this columnar structure. The columns are perpendicular to the chief cooling surface, and thus in a level intruded sheet, or in a flow of lava, they stand vertically, while in a dike they tend to be horizontal, that is, perpendicular to the plane of greatest extension of the rock mass. Thus some dikes, exposed as walls by erosion, resemble regularly piled cordwood. In other

masses their position depends on the directions taken by the cooling planes; in volcanic necks they may be perpendicular, or in them, as well as in other rock-bodies, they may be curved, or even radiant.

The cause for the structure appears to be this. When the igneous mass is cooling slowly and regularly, centers of cracking tend to occur on the cooling surface at equally spaced intervals. From each interspace three cracks will form and radiate outward at angles of 120°. These, intersecting, produce regular hexagons, and the cracks penetrating inward make the columns. But, as the contractional centers are not always equally spaced, four-, five-, and even seven-sided columns occur. The columns again, contracting lengthwise, break into sections. The same principle is seen in the manner in which drying mud-flats crack into polygonal shapes. See Fig. 210.

Jointing in Metamorphic Rocks. — The jointing seen in these rocks depends largely on their nature. In the massive gneisses it is very much like that in granite, while in the very fissile and schistose rocks, such as slates for example, it is more like that observed in many sedimentary beds. In general it may be said to resemble that in the sedimentaries, but to be less perfect; as a rule the metamorphic rocks are apt to be much jointed.

Great Rifts. — In addition to the divisional planes in the rocks, which have been described above as joints, they are penetrated by fractures or rifts on a great, and in some cases vast, scale. The most direct evidence of these great rifts is seen in the phenomena of faults, as described later, but the indirect evidence of their existence is also shown in a number of ways. Thus, the alignment of volcanoes in many places suggests it (page 217), as do also springs (page 157); the arrangements of drainage in some places, and the direction of mountain ranges in others, also lead us to infer their existence. The outer crust of the earth appears, indeed, to be everywhere divided into great blocks by these fractures or rifts, see pages 241 and 245. Usually the walls of the rifts are pressed tightly together, in many cases they are healed by deposits of mineral matter in them. In a few instances they would be open save for the débris which has tumbled into them, or been broken from their walls, and which fills them up. Any further discussion of them leads us inevitably to the subject of faults.

Faulting

Faults. — When rifts have been formed in the rock masses of the outer shell of the earth, movements along the face of such rifts may occur at the time of their formation, or subsequently, giving

rise to displacements of the rock masses, compared with their former positions. Such displacements are called *faults*, and faults are a matter of great importance in geology. We have already met them in discussing movements of the earth's crust and earthquakes, and we shall observe them playing very important parts in our consideration of mountain ranges and of ore deposits. They are a more or less constantly recurring feature which must be dealt with in the proper understanding and delineation of geologic structures. As geologic phenomena they are, therefore, of interest, not only from the scientific, but also from economic and technical standpoints.

Faults are frequently described and treated as if they were connected only with the stratified rocks. This is a mistake, for while they are most easily observed in such rocks, and thus, perhaps, seem to occur most often in them, they are also found in igneous and metamorphic rocks and may give rise in them to important structures and be of great technical consequence.

The Fault-surface. — The fracture along which movement and dislocation has occurred is often spoken of as the fault-plane. While it is, perhaps, natural to speak of it as a plane, it is probably rarely flat for any distance, but more or less warped, broken, and frequently offset, and it is, therefore, better, and causes less misapprehension, to term it the *fault-surface*. Moreover, the movement in faulting may occur, not upon one determined surface, but upon a number of more or less closely adjacent ones, producing a fault zone, in which the various slipped blocks may make in the aggregate the total displacement. Such a distribution is sometimes called *step-faulting*. The masses of rock involved in fault movements are generally of such size and weight, and often so compressed together, that the motion of one fault face on the other, along the faulting surface, takes place under tremendous pressure. As a result of this rubbing under pressure, the rock faces are smoothed and striated, and not infrequently beautifully polished, and such polishings and groovings are known as *slickensides*. The line of intersection of the fault with the plane of the horizon is called the *strike*, or trend, of the fault, just as we speak of the strike of the bedding plane of upturned sediments (page 299). The surface of faulting is rarely exactly vertical, it is apt to be inclined, and, in some cases, so much so, that it may approach horizontality. The angle of incidence between the fault-surface and the vertical plane passed through the line of strike is the *hade* (see page 314); the angle with the plane of the horizon is the *dip*, as with strata, and this is the complement to the hade. As it is more natural to

think of fissures with reference to vertical directions, hade is used, possibly, more conveniently, though perhaps less commonly, than dip. In the case of an inclined fault the side which tends to be

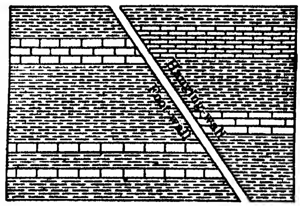


Fig. 264. — Diagram to show fault terms.

above is known as the *hanging wall,* the other as the *foot-wall.* See Fig. 264. If one were to imagine the fissure opened and himself descending it, the appropriateness of these old mining terms becomes obvious.

Fig. 265. — Fault in shale; the drag and curvature of the beds show that the left side has gone down, the right up. Little River Gap, Tenn. A. Keith, U. S. Geol. Surv.

A fault is not infrequently composed of numerous parallel ruptures and slips. While the fracture is generally tightly closed it may, on occasion, have opened and been filled with fragments from above, or the grinding of the walls upon one another may produce a zone of broken material, and such angular, crushed rock filling a fault is known as *fault-breccia.* Examination often shows also that when stratified beds are faulted, as shown in Fig. 265, there is a curvature of them at the fault-surface resulting from the drag. Such curva-

ture, as illustrated, may be a useful aid in determining the directions of motion on the opposite sides.

Motion on the Fault-surface. — Experience shows that if we consider one side of a fault to stand fast, motion on the other side may be up, down, side-wise, or obliquely. Thus in Fig. 266 the lettered plane may represent the fault face, which for convenience we may consider to remain at rest, the other side which undergoes motion having been removed to expose it. If we suppose some

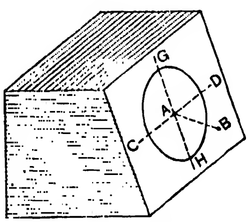


Fig. 266. — Diagram to show possible motion in faulting.

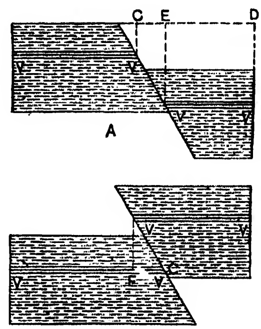


Fig. 267. — Normal and reverse faults.

particle A, for instance a pebble, to be cleft by the fault-fracture, then one part A remains in its original place and the other part B, embedded in the other face, may be carried in some direction by the faulting. This line A–B is the direction and amount of the fault. B may be carried from A vertically up or down on G–H, or horizontally on C–D, or in any radial direction, and usually is taken in some more or less oblique course A–B.

Normal and Reverse Faults. — If we consider faulting as having taken place merely in a vertical plane then two important cases may arise. In A, Fig. 267, the hanging wall has apparently slipped down with reference to the foot-wall; a fault of this kind is known as a *normal* fault. In the other case, B in the figure, the hanging wall has apparently been crowded up over the foot-wall, and a fault of this kind is called a *reverse* fault. It will be noticed that with the normal fault a particular layer V–V has been lengthened apparently by an amount corresponding to the gap C–E, while in the reverse fault it has been shortened by an equivalent overlap. With reference to what has been supposed to be their origin, normal faults are sometimes called *tension* faults and reverse ones *compression* faults.

It will be observed that in the above statement normal and reverse faults are said to be *apparently* formed by vertical up or down movements. There can be no doubt but that in many cases the direction of movement is approximately vertical, that is, along *G–H*, Fig. 266, or nearly so, but in very many other cases it is not; the motion is oblique along some line *A–B*, and we may even have normal and reverse faults formed by a simple horizontal shove along *C–D*, Fig. 266. This may be seen by careful observation of Fig. 268. The movement of the front block to the right has produced an apparent

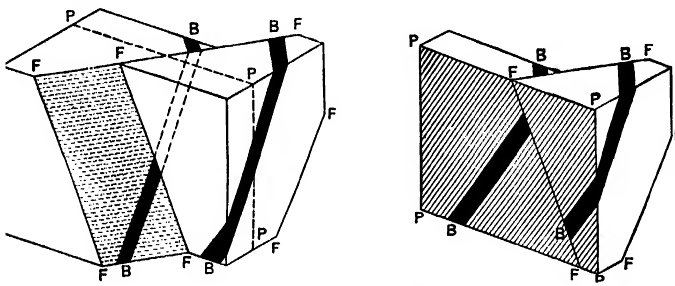


Fig. 268. — To illustrate how normal faulting, as seen in a vertical plane *PP*, may be caused by simple horizontal shoving on the fault-surface *FF*. The particular stratum *B* in *PP* (right-hand figure) appears to have slipped down. Modified from Ransome.

normal fault; had the movement been to the left we should have had an apparent reverse fault. The terms normal and reverse should, therefore, not be used in the sense of conveying ideas of particular kinds of motion, but merely to indicate the results achieved, as shown in a vertical cross section of the faulted parts.

Components of Faulting. — In order that we may be able to understand and define the geologic structure, where faulting has occurred, it is necessary that we should know the amount and direction of what we may term the components of a fault. This may be understood by aid of the adjoining diagram, Fig. 269. In this *A–G–E–F* represents the horizontal plane, *A–F* is the strike of the fault, that is, its intersection with the horizontal plane, and *A–D–B–F* is the fault-surface. Let us suppose that the motion has been such that a particle *A* has been carried to the position *B*, then the line *A–B* joining these two positions is the *displacement*, or *slip;* and no matter what path the particle may have followed, *A–B* is the resultant, and its length the measure of the slip. The line *A–B*, however, in order that it may be fixed and determined, must be referred to known axes and this is done by referring it to three planes at right angles to each other. The first is the plane of the horizon, *A–G–E–F*, the second is a vertical plane parallel to the strike, *E–G–D–B*, and the third is the vertical plane, *F–E–B–H*, at

right angles to the last one. Now the line *F–E* gives the amount of motion along the horizontal plane at right angles to the strike *F–A*, and this is known as the *heave* of the fault, the line *E–B* is the amount of vertical motion and is called the *throw* of the fault, while *F–A*, or *E–G*, the amount of motion along the strike in the horizontal plane, may be termed the *shove*, or *strike-slip* of the fault.

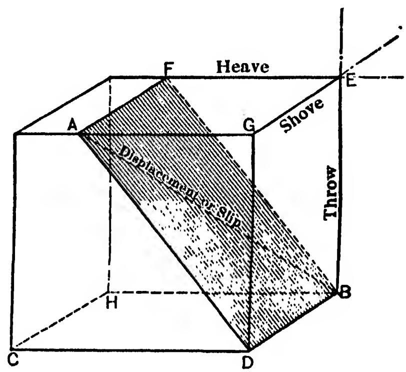


Fig. 269. — Diagram to illustrate and define the components of faulting. Fault-surface shaded.

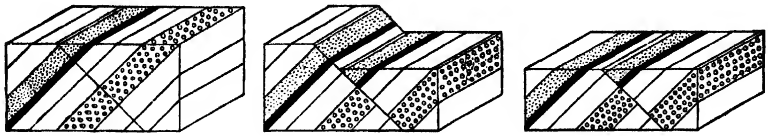
The intersections of the three planes give the three right-angled axes *F–E*, *E–B*, and *E–G*, meeting in the common point *E*, and these may be termed the *component axes* of faulting. The directions and intercepts on these axes being known, the displacement can be calculated, and the problem of the fault solved.

The heave and throw of faults are the components commonly recognized, as we shall presently see in considering them in stratified rocks. The reason is that the dislocation is most easily seen in a vertical section *A–G–D–C*, and in this the particle *A* has apparently moved from *A* to *D*, while the amount of shove *B–D*, or *A–F*, may not be at all evident on the surface. The shove is, indeed, as a rule, difficult to estimate in most faults and often it cannot be determined at all.

It is clear that a fault might take place without shove, the movement being wholly in the vertical plane *A–G–D–C*; it might also take place with a vertical fault-surface *E–G–D–B* and in this case there would be no heave; there might be shove, but this might also be wanting and it would be a pure *throw* fault. We might also have a simple shove, without throw or heave. The last case, in which the fault-plane is horizontal and there is pure heave without throw or shove, while theoretically possible, hardly seems practicable, the nearest approach to it are certain faults described later under thrusts.

A good case of the throw of a normal fault is seen in Fig. 188, and of shove without throw in Fig. 189.

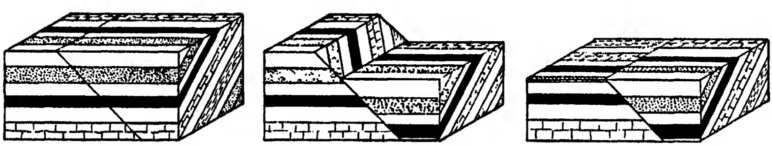
Faults in Stratified Rocks. — Although faults occur in all kinds and combinations of rocks, they are best, and therefore, most frequently, observed, in stratified beds, on account of the strongly



A B C

Fig. 270. — Model illustrating strike-faulting in stratified rocks. *A*, before faulting; *B*, after faulting, fault-scarp still uneroded; *C*, surface levelled by erosion.

marked stratification which they disarrange. With relation to this structure, faults may be *strike-faults,* when the strike of the fault and that of the strata are parallel, or nearly so, as illustrated in Fig. 270; or they may be *dip-faults,* when at right angles to the



A B C

Fig. 271. — Model illustrating dip-faulting: *A*, before faulting; *B*, after faulting, fault-scarp uneroded; *C*, surface levelled by erosion, showing offsets of strata.

strike of the strata, or nearly so, as shown in Fig. 271; or they may be *oblique faults,* when at 45° to the strike of the beds, or approximately so.

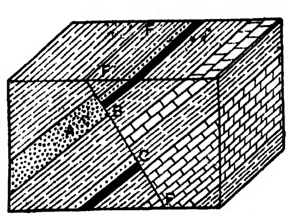


Fig. 272. — Diagram illustrating concealment of strata by strike-faulting.

In the cases shown in the figures the faults are normal ones; they may also, of course, be reversed faults. They are also depicted without real shove, yet it will be noted in Fig. 271 *C* that, apparently, shove has occurred, causing the beds to offset. This sudden

offsetting of strata, traced along their strike, is one of the surest indications of a dip-fault. Strike-faults are more difficult to perceive and may be easily overlooked; they may cause deception as to the thickness of strata by producing apparent repetitions. See Fig. 270 *C*. Thus, in traversing strata a repetition of a certain set should lead to suspicion of strike-faulting. On the other hand, strike-faults may conceal strata after erosion has occurred. Thus in Fig. 272, where a reverse fault *FF* has occurred with movement from *C* to *B* and subsequent erosion, there is no outcrop of the stratum *A* at the surface.

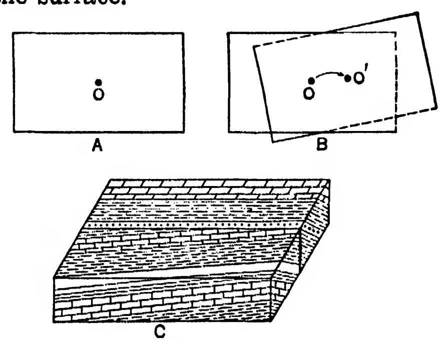


Fig. 273. — Diagram to illustrate rotary motion in pivotal faults. *A*, before faulting; *B*, after faulting; *C*, effect on outcrop after erosion.

Rotary Faults. — The movement of one side of a fault-face on the other side may be attended by rotary motion, as illustrated in Fig. 273, showing the original and final positions of the fault-faces as projected on a vertical plane. Faults of this nature are known as *rotary* faults. They are sometimes indicated, when strike-faults, by the strike of the strata on opposite sides of the fault-line not being parallel, and in dip-faults by a sudden change in the direction of the strike of strata as the fault-line is crossed.

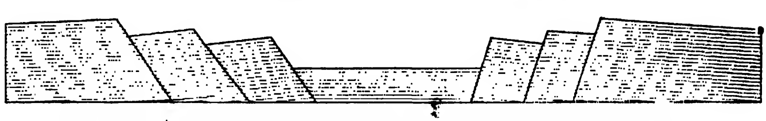


Fig. 274. — Illustrating the forming of a trough by normal faults.

The Magnitude of Faulting. — The scale on which faulting has taken place varies within the widest bounds. It may be but a fraction of an inch as illustrated in Fig. 204, it may be a number of feet and from this up to many thousands. Normal faults attain these magnitudes in the Appalachians, while in the Plateau region faults of several thousands of feet throw are not uncommon, the fractures extending for hundreds of miles, and the fault-scarps, being yet uneroded, form lines of cliffs which give character to the topog-

raphy. The Great Basin region presents on a colossal scale the phenomenon of faulting, the area between the Sierra Nevada on the west and the Wasatch on the east being divided into huge blocks by fractures running for many miles, and the sinking of these blocks has produced faults of great dimensions. This will be further alluded to under mountains. Sunken tracts of country due to normal down-faulting, as illustrated in Fig. 274, form what are called *troughs* (German *graben,* French *fosse*) and are illustrated in the valley of the Rhine, the great Rift Valley of Africa with its lakes, and many other places. Such troughs, *graben,* are the direct opposite to *horsts,* which are mentioned on page 243. The relation between them and igneous outflows and intrusions is mentioned on page 225.

Fig. 275. — A thrust-fault on a small scale. Near Houston, Okla. J. A. Taff, U. S. Geol. Surv.

Thrusts and Thrust-faulting. — Reverse faults are most commonly found in those regions where crushing and folding of the earth's shell has taken place, and the stronger the folding or crushing has been, the greater and more evident the reverse faults are. Thus, it is especially in the stratified rocks in mountain regions that these results are seen, as in the southern Appalachians. The careful and detailed study of old mountain areas has disclosed the fact that

these reverse faults have sometimes occurred on a tremendous scale, and with the fault having a comparatively low angle of inclination, even being in some cases nearly or quite horizontal. Reverse faults thus having a gently inclined to horizontal fault-surface are known as *thrust-faults* or simply *thrusts,* see Fig. 275, and they may be of such magnitude and importance that by some geologists they are considered quite aside from faults, and in a class by themselves. The fault-surface in this case is spoken of as a thrust-plane.

Such thrusts have been discovered and studied especially in the Alps, in Scotland, in the northern part of the Scandinavian peninsula, in the southern Appalachians and in the front range of the Rocky Mountains in Montana and British Columbia. The distances which the lower formations may be pushed and made to over-ride the later ones are sometimes amazingly great, ranging from a number of miles up to 70, or 100, or even more. In Fig. 276 is seen a section representing a portion of the great thrust along the front ranges of the Rocky Mountains in northern Montana. The deciphering of such great displacements is one of the triumphs of modern geological research.

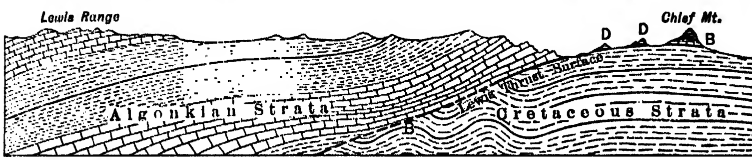


Fig. 276. — Section showing the thrust in northern Montana, whereby very old geologic formations of the Algonkian are made to over-ride the much younger beds of the Cretaceous. *BB* is the surface of thrusting; *DD* and Chief Mountain are erosional remnants of the Algonkian resting on, and surrounded by, the younger Cretaceous. Displacement by thrusting observed, 7 miles; actual amount unknown. Generalized after Willis.

Topographic Results of Faulting. — If a fault of some considerable magnitude were to occur suddenly, it would naturally be marked at the surface by a corresponding displacement, giving rise, if vertical or nearly so, to a cliff, which is commonly called a *fault-scarp.* Such fault-scarps are not unknown, and have been described from a number of places. The connection of quickly formed faults with earthquakes has been previously alluded to (page 244) and an illustration, Fig. 277, shows a fault-scarp which has just been formed with resultant earthquake shock.

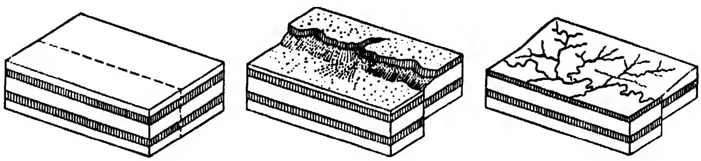
Such scarps may be called *initial fault-scarps.* As the process of weathering and erosion works more actively, in general, on the uplifted side, the scarps tend to become dissected, eroded, lowered, and to retreat from the fault-line. Thus they may pass through youthful, mature, and old stages. Finally, the difference in elevation on opposite sides of the fault-line may be worn away completely, and thus all topographic expression, initially due to faulting, may be

Fig. 277. — Waterfall due to sudden forming of a fault-scarp across a stream bed; part of movement which caused a great earthquake. Balboa Bay, Alaska. W. W. Atwood, U. S. Geol. Surv.

obliterated. This would finish one cycle of erosion on a faulted surface. See Fig. 278.

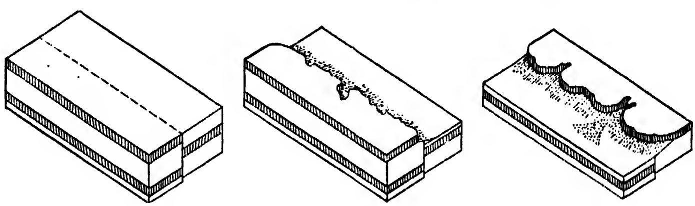
If now the whole mass should be uplifted with little, or without relative, displacement of the parts and thus a new cycle of erosion inaugurated, similar to that explained under the rejuvenation of rivers and river-work, then the agents of erosion might find on opposite sides of the fault-line rock structures of quite different hardness and ability to withstand their attack. Thus, one side might be lowered so much more rapidly than the other as to leave the latter standing as a cliff or escarpment. This latter would be due, however, not to the initial faulting movement, but to subsequent differential erosion in the following cycle on opposite sides of the fault-surface. Such cliffs deserve, therefore, a different name

and have been termed *fault-line scarps* by Professor Davis. They may develop on the side of the block that was originally uplifted, and are then termed by him *resequent,* or they may form on the opposite block, and face toward the uplifted side, and are then called *obsequent.* The varying resistance to erosion on the opposite sides of



A B C

Fig. 278. — Shows the origin, development, and history of an initial fault-scarp. *A*, block of strata containing two harder, more resistant intruded sheets of trap, before displacement. *B*, after faulting and some erosion; the fault-scarp has become mature, and has retreated from the fault-line. *C*, approaching the end of the first cycle of erosion; the fault-scarp has been obliterated.



A B C

Fig. 279. — Development of fault-line scarps. *A*, faulted block of strata commencing a second cycle of erosion; intruded trap sheets more resistant than the enclosing beds; uplifted block to the right. *B*, after erosion; a *fault-line* scarp has formed which faces toward the uplifted block and is therefore *obsequent*. *C*, continued erosion has carried away the top trap of *B* and its obsequent cliff and a new one has formed facing the other way, toward the sunken block; this is a *resequent* fault-line scarp; compare *B*, Fig. 278.

the fault-line determines naturally which will form, and the course of a very long and old fault-line might be marked in one place by resequent, and in another by obsequent, scarps. Finally, through the completion of another cycle of erosion these also in turn might be worn away. An understanding of them may be gained by observing Fig. 279, which may be considered a later development of Fig. 278.

The east slope of the Sierra Nevada, the west slope of the Wasatch, and the steep faces of the intervening north and south ranges of the Great Basin, as previously discussed, are held to represent more or less eroded fault-line scarps. At the west base of the Wasatch Range some of the faulting has occurred so recently that fault-scarps may be seen uneroded in the soft fans of alluvial material brought down by the streams. The Plateau region, through which

the Colorado River cuts its way, is dominated in its topography by a series of great faults, whose almost uneroded scarps form prominent cliffs. They have been described as fault-scarps, but are very probably fault-line scarps developed in a second cycle of erosion. One of the most striking instances of initial fault-scarps is found in the great Rift Valley of central Africa whose walls form prominent escarpments for great distances. Examples on a smaller scale are very common. Thus the sunken tract of sandstones and intercalated trap sheets between New Haven, Connecticut, and Springfield, Massachusetts, is divided into a series of tilted blocks by faulting. It has passed through one cycle of erosion, in which the initial fault-scarps have been eroded away; it is now in a second cycle and the resistant outcrops of trap form prominent ridges, fault-line scarps, both obsequent and resequent, which dominate the topography and reveal the system of faulting which divides the displaced masses. See Fig. 281.

Erosion of Faults. — On the other hand, it is also true that in many places the most profound faults exist, with displacements amounting to thousands of feet, of which there is no trace so far as the surface is concerned, both sides being at the same level. We must conclude in such cases that great erosion has occurred, that the first cycle has been completed, or possibly that the growth of the displacement has been slow enough to be controlled by it. It seems not unreasonable to believe that the latter has often occurred, for we can scarcely imagine that the formation of great faults, with thousands of feet of displacement, has been a sudden process, but rather the gradual yielding of the shell of the earth in response to the forces brought to bear upon it during long periods of time. The detection of eroded faults, which may be a matter of the highest importance in understanding the structure of a region, is often one of great difficulty, demanding the greatest skill and geologic knowledge.

The detection of faults which do not show any distinct topographic relief is accomplished in a variety of ways. The most common and obvious is the disturbance, or discontinuity, produced in the structure of stratified rocks, as previously explained. This applies to metamorphic rocks also, but to a lesser extent, because their structures are more complicated and confused, less clear and evident. In homogeneous masses of igneous rock it may not be possible to detect faults, yet even here discontinuity in certain features which they may possess, such as dikes and veins, may lead to the discovery of faults in them.

Origin of Faults. — The immediate cause of faults is comparatively simple and generally agreed upon; they are due either to compression, or to stretching, of the outer shell of the earth. In the first case, through the stress which accumulates from the increasing force of the thrust, the rock masses are strained to a point

where they can no longer resist, but must give way. Relief occurs through readjustment by movement, either along the surfaces of some previous fracture, or by the formation of a new one. Some effects produced by such movements have been considered under earthquakes. It is also clear that faults of this nature will occur chiefly in places where folding of the strata is a prominent feature and thus, as we shall see later, in mountain ranges. If the process takes place on a great scale, we may have overthrusts developed.

On the other hand, where segments of the outer shell are (relatively) uplifted, as in the formation of horsts (see page 243), the strata may be under tension, and the stretching find relief by fracturing and faulting, the latter produced by the gravitative settling and readjustment of the fault blocks. Thus over wide regions where the strata are not otherwise disturbed, as in the Colorado Plateau, they may be penetrated by fractures and show great displacements along them. And also in the upper portion of up-arching folds there may be tension and cracking, with subsequent gravitative settlement and faulting.

It is natural to think that in regions of folded rocks reverse faults would be the chief, or only kind developed, but, although it is true that they are essentially confined to such places, the converse of this, that normal faults are found only in unfolded strata, is by no means the case. On the contrary, they are also abundant in folded and dislocated areas, as well as in those where the strata are still horizontal, or nearly so. The great majority of faults, in fact, appear to be normal ones, due to gravitative settling for the most part, and resulting in elongation of the crust, and to thus deserve the name; but it should not be forgotten, as shown on a previous page, that normal and reverse are only terms for certain results, and that, for example, an apparently normal fault may be produced by compression. In further explanation of what has been said above, if a segment of the earth's shell subsides, it is evident that the beds near the edges of the block will be, subjected to tension, and, eventually, to rupture and gravitative faulting. The same is as true, as stated above, if a segment rises, the relative displacement and stretching being the important feature. Thus, in the sinking areas along coast-lines which are receiving heavy deposits of sediment, such tensional effects must occur. Also the sinking, or rising, of such areas may be, and probably is, not uniform over their extent, and thus torsional stresses due to the warping will be set up, with fracturing and readjustment of the blocks and consequent faulting. We can hardly imagine movements of the earth's outer shell to take place without either compression, tension, or torsion occurring and producing more or less faulting. As a consequence, all parts of it that are open to our inspection display this phenomenon to some extent.

The *ultimate cause* of faulting evidently depends on those processes within the earth which give rise to compression, or tension,

and to movement of segments of its outer shell. They are most strikingly displayed in the formation of its chief features of relief, in mountain ranges for example, and faulting may be considered only a minor and attendant result of their operations. We shall wait, therefore, until the grander results of these processes have been discussed, before considering them and venturing from the known into the realm of the unknown.

CHAPTER XV

MOUNTAIN RANGES: THEIR ORIGIN AND HISTO

Definition of Mountains. — No exact limit can be set as to the h^ight an elevation should rise above the surrounding country in order that it may be properly termed a mountain, for this is largely a matter of comparative relief, and the mountains of one region where the relief is small would be only hills in another where it is great; they may vary from a few hundred feet high, up to the loftiest summits in the world. Although we frequently read of the "everlasting hills," at the very outset it should be understood that mountains, like all forms of terrestrial relief, are not permanent structures, but are always wasting under the attack of atmospheric agencies, though not infrequently renewed by repetition of the same processes which originally caused them, as will be shown in later discussions.

The Grouping of Mountains. — When we consider the arrangement of mountains we find that they may be irregularly disposed in *groups*, such as the Catskill Mountains in New York, the Judith Mountains in Montana, the Black Hills in South Dakota, or, as is more commonly the case, they may be aligned in *ranges*, such as the Sierra Nevada, the Caucasus, etc. Such ranges may consist of a single ridge, but more often they are compound, composed of a variety of ridges whose general direction is parallel, giving a united trend to the whole range. As we shall see later, a range is to be regarded as a *geologic unit*, formed at a definite time by a set of processes operating toward this end.

A series of ranges, independent of one another, but formed approximately at the same time during a given geologic period and having a common general trend, is known as a *mountain system*. So in the Rocky Mountains a series of ranges constitutes what Dana has termed the Laramide Mountain system, while in the eastern United States the Appalachian Range, running through Pennsylvania southward, the Acadian Range of Nova Scotia and New Brunswick, and the Taconic Range of western Massachusetts together constitute the Appalachian System.

A combination of mountain systems, such as those of the Andes, constitutes a *cordillera*. Thus the whole vast mountainous region

extending from the eastern front of the Rocky Mountains to the Pacific, and from Mexico northward through the United States and Canada into Alaska, with its various chains, systems and ranges, such as the Rocky Mountains, the Sierra Nevada, the Cascade and Coast Ranges, etc., is collectively known as the *North American Cordillera.*

Origin of Mountains. — There are three different kinds of agencies to which mountains owe their origin and these are igneous agencies, erosion, and movements of the earth's crust. As we shall see later, no sharp line can be drawn between the different mountain forms produced by these three agencies, but for the sake of convenience and illustration we may distinguish the following types.

Mountains Formed by Igneous Agencies. — These may be subdivided into two classes. In the first the elevations have been produced by *extrusion* of material, and these are illustrated by volcanoes. Some of the loftiest peaks in the world, like those of the Andes (up to 23,000 feet) and Kenia (17,400) and Kilimanjaro (19,700) in Africa, are of igneous rocks. They are situated, however, in high plateaus, for the Andes 12,000–14,000 feet, in Africa about 6,000 feet, which accounts for a large part of their great height. Many oceanic islands are really great volcanic mountains seated on the ocean bottom and rising, as in the case of Hawaii (30,000 feet), to tremendous heights above their base. See page 116.

Mountains produced by *intrusion* of igneous material into areas of stratified rocks are of the second class, and would be illustrated by laccoliths (page 316) and also in part by necks and stocks (pages 318, 319), although in these cases the work of erosion has also, as a rule, played an important rôle in developing the mountain forms by cutting away the softer sedimentary material, and leaving the more resistant igneous masses exposed. The best examples of laccoliths are found in the region of the Rocky Mountains, especially in outlying districts not far from the ranges of the main chains. Thus the Henry Mountains in Utah, the West Elk Mountains in Colorado, and the Little Belt and Judith Mountains in Montana are mountain groups produced by laccolithic intrusions. In some cases, as in parts of Wyoming and Montana, there are domed hills of sedimentary beds, in which no igneous rock is visible. By analogy, we place these in this same class, in the belief that the cover has not yet been eroded. As we shall see later, igneous intrusion has also helped in the development of many of the great ranges made by folding.

Mountains Formed by Erosion. — It may happen in the general

erosion of an uplifted area of country that some parts and places during the process of lowering are left projecting, and these may be of size, sufficient in relation to their surroundings, to be designated as mountains. Some of the buttes in the western United States (page 36) are examples of this. The Catskill Mountains in New York State have been generally referred to as a mountain group of this character, etched out by erosion from a plateau of uplifted sedimentary strata. Looking from its brink into the Grand Canyon of the Colorado, one sees a great number of pointed remnants of erosion rising from the depths of the chasm. If they were removed from this stupendous gorge and placed on a plain many of them would form large mountains, and the aspect which they present, as one looks upward at them from the bottom of the canyon, is that of a high and rugged mountain range. They have been formed from the dissected rim of the great plateau, and are therefore in the same class as the Catskills. Thus from the erosive dissection of uplifted masses, or plateaus, mountains may be made.

Such uplifted plateaus may consist of sedimentary beds in horizontal position, or of these with associated sheets of lava, or they may be made of folded and disturbed strata which have been previously peneplaned by erosion. The mountain forms etched out by erosion differ in the two cases. In the first they are often flat-topped or pyramidal with slopes like those seen in Figs. 23 and 34. In the second they are apt to be long ridges with crests of the harder rock strata, often in parallel groups, with gaps or notches cut through them by the older consequent master streams, whose tributaries drain subsequent valleys between the parallel ridges. Mountains thus formed by the dissection of a former peneplain are to be seen in parts of the Appalachian Highlands, as will be seen later.

Mountains Formed by Movements of the Crust. — The types of mountains which have been considered in the foregoing discussion, although of geologic interest, and in some places forming groups or masses of considerable size, are relatively of small importance compared with the ranges produced by movements of the earth's shell. For it is especially by this agency that the great mountain ranges, which in so many places constitute the dominating features of relief of the earth's surface, have been made. According to the nature of the movement and its results, we may divide many ranges into two classes, one in which they have been made chiefly, or entirely, by dislocation, or *faulting*, resulting in vertical uplift of crust blocks, and one in which they have been produced by wrinkling, or *folding*, of the earth's shell. In the former case the ranges are the exposed edges of great tilted blocks of the outer shell, and in allusion to this

fact are sometimes called *block mountains*. In the second case, the structures made by folding are typically anticlines and synclines (page 296) and they may be designated as *folded* ranges. But, although we can find good and clear examples of these structural types, on the other hand in many cases, and these include some of the greatest ranges, like the Alps, both folding and crushing, that is to say, dislocation or faulting, have worked together to produce them. Sometimes both agencies have been operative, sometimes one has been more important than the other, and if we add that often intrusions of magma have also aided in the process it can be easily seen that mountain ranges of great structural complexity have been produced.

From what has been stated in the foregoing, it may now be seen that different types of mountains, according to the agencies producing them and their structural results, may be summarized in tabular form as follows:

Agency	Mode of Operation	Structural Results
		Single, or grouped mountains.
Igneous......	Built up by *extrusion of* material.	Volcanoes, Lava domes.
	Upraised by *intrusion* of material.	Laccoliths.
Erosion......	Masses etched out and left in relief.	Dissected plateaus.
		Mountain ranges
Movements of the crust	Produced by dislocation, or faulting, of blocks.	Block mountains.
	Upraised by folding of crust.	Folded types.
	Combinations of above.	Complex structural types.

Although, as mentioned above, clearly defined examples of each of these types are not infrequent, it is true that all gradations exist between them, and that types of compound nature are most frequent, as will appear in the following sections.

Block Mountains. — As stated, these have been formed by the faulting and tilting of great blocks of the earth's crust. Their structure is most clearly seen in regions of stratified rocks whose beds were previously horizontal; the tilted block then presents a more or less dissected fault-scarp rising to the crest line on one side and a much gentler slope on the other, the beds dipping in the direction of the gentler slope. More commonly the same structure of tilted blocks occurs in regions where the strata have been previously folded and, perhaps, injected with igneous masses, and then

greatly reduced by long continued erosion. In this case the structure is not so directly evident, but may be inferred from the nature and arrangement of the block ridges, and from certain characteristic physiographic features which they exhibit, such as the straight base-line from which the mountain slopes arise from the plain below, and which may cut off the ends of the descending spurs with abrupt faces. This type of mountains is illustrated by the north and south ranges in parts of the region of the Great Basin in the western United States, lying between the Wasatch Range on the east and the

Fig. 280. — Diagrammatic section east and west through the Great Basin, showing how the structure is dominated by faults.

Sierra Nevada on the west. An east and west section of this is diagrammatically shown in Fig. 280. The production of these mountains by normal faulting has been already alluded to, pages 365 and 369.

The structure here shown is thought to be most typically developed in the northern part of the Great Basin. Between the great wall of the Sierra to the west, and the Wasatch on the east, the country is filled with many north and south mountain ranges, which are rather narrow and from 10 to 50 miles in length. They may be readily seen in any good atlas on the maps of Nevada, Utah, and adjacent states. Between them lie plains and in places lakes, some fresh but others salt, the region affording the most conspicuous examples of interior drainage in North America, as previously explained under salt lakes. See Fig. 294.

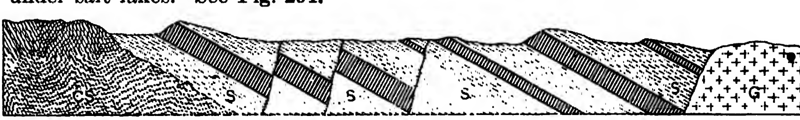


Fig. 281. — Diagrammatic east and west section across Triassic sandstone and included sheets of trap rock. Vertical scale (and thickness of trap) exaggerated. *CS*, crystalline schists; *G*, granite; *S*,*S*, sandstone and shale; heavily black-lined, trap. Near New Haven, Conn.

The history of the Great Basin region does not begin with the time when block-faulting took place. Long prior to this were periods of deposit of sediment, of folding and faulting of strata, and, no doubt, of mountain elevation, followed by great erosion, and, perhaps, peneplanation. It was only after this that the block-faulting began; as a consequence the structure of the ranges is complex, and in many cases not yet worked out. The plains of débris derived from their erosion, which lie between them, as suggested in Fig. 280, conceal the structure of the areas beneath them. There is good

reason for thinking that some of the faulting is not only recent, but that it has continued into the present. But, although the structure of these ranges may be complicated, and several agencies may have contributed to their present topography, it is true, in the main, that the faulting of the region and the tilting of the blocks produced by it, have been the dominant agents which have given rise to most of these ranges.

Block mountains made by faulting and erosion occur also in other parts of the world, and many such examples could be quoted. Thus they are found in south Norway, where in places heavy sheets of igneous rock have preserved the tilted sediments beneath them from erosion and form the crests and backs of one side of the ridges. The same structure is repeated on a small scale in the sunken area of Triassic sandstones running northward from New Haven, Connecticut, to Springfield in Massachusetts. Here also heavy sheets of igneous trap-rock have resisted the erosion and form the crests and backs of the ridges, as may be seen in the accompanying figure, 281.

Folded Mountain Ranges

Introduction. — All the great mountain ranges of the world belong in the classes of folded or of complex structural types. In North America the Appalachian Mountains, the Ouachita Range of Arkansas, the Coast Range bordering the Pacific, and in Europe, the Jura Mountains in Switzerland, are good examples of folded ranges, whereas the Rocky Mountains, the Alps, the Urals, the Himalayas, and the old mountains of Scotland and Norway present illustrations of the complex types. It is especially in these kinds of mountains that the greatest exhibitions of geologic phenomena are seen and the lessons, which geology as a science teaches, may be learned. If one desires to know the history of a region, one turns naturally to its mountain ranges, for here may be found the upturned and dissected strata, a study of whose kinds, thickness, and fossils throws light upon past events, while their foldings and dislocations show the nature and results of those great dynamic agencies, which from time to time have operated upon the outer portion of the earth, and given to it the broad distinctive features which characterize it to-day. They are also the theaters in which many of the forces, which are now modifying the surface of the earth, play their most active rôles, and we can there see the work of erosion, as carried on by water in its varied forms of rain, frost, snow, ice, streams, glaciers, etc., most extensively shown. In most cases, the making of the great ranges has been accompanied, in addition, by igneous activity, and they have been the seat of intrusions and extrusions of molten magmas which have added their quota to the masses of material and to the complexities of structure that the ranges present. It is by reason of these things that they offer prob-

lems of the highest interest and importance to geological science, and, therefore, merit most serious consideration.

Divisions of Mountain History. — The treatment of the subject logically begins with the folded ranges, for they are the most simple, and then proceeds to a consideration of the more complex types. Their history most naturally divides itself into three portions, as follows:

a, The *pre-orogenic* period, in which processes and their results are preparing the place and material for the future range; *b,* the *orogenic* period (see page **241**) in which the range is made; and *c,* the *post-orogenic* period, during which the range has been subjected to various modifications, chiefly those of erosion, which have brought it to its present condition. It must be clearly understood, however, that no exact boundaries, either of time or of the events occurring, can be drawn for these periods; although they are convenient distinctions for purposes of discussion, they, in truth, merge gradually into one another, so that the whole sequence, like the profile of the range itself, represents a gradual culmination and decline.

Pre-Orogenic Period; Thick Strata. — The detailed examinations which have been made of folded mountain ranges prove that they are composed of masses of very thick sedimentary beds, whose folding and crushing together along a definite axis has produced the elevated tract of country. The length of this axis is that of the range, which may be 50 miles, or 1000 miles, or even more; the breadth of the tract may be up to 250 miles or more. The maximum thicknesses of the strata, which have been determined in some of the great ranges, are indeed enormous; in the Appalachians nearly 25,000 feet, and as much in the Coast Range, while in others it has been estimated as even greater. But when traced away from the mountain tract, the beds, which the fossils show to be of the same period of deposition, thin out and may even disappear entirely, to be replaced by rocks of a different nature and age. Thus the strata composing the Appalachians have thinned down in the region of the Mississippi to 4,000 feet (4,000 in Indiana, 5,000 in Iowa), while toward the Atlantic to the eastward of a line from northern New Jersey southwestward to Georgia and beyond, they are cut off by faulting and erosion and are entirely wanting. It is probable that in some cases the thickness reported in mountain districts may be due in part to the swelling of the beds caused by the crushing together which they have experienced, and that the first estimates (for the Appalachians 40,000 feet) were thus exaggerated, but the fact stands, nevertheless, that the strata involved are of great thick-

ness and of the order of magnitude mentioned above. From this and other facts important conclusions regarding the pre-orogenic period may be drawn, as discussed in the following paragraph.

Preparation for the Future Range. — From the general principles which have been previously explained, it will be clear to the student that a line of thick heavy sediments can be laid down only in a place of one kind, along the margin of a land that is being actively eroded. If the sediments were entirely of a marine origin, if they consisted solely of lime deposits, of chalk and limestone, this would not be true, for they might then, under favorable conditions, have accumulated in the open sea. But consisting as they do in the great ranges of mingled beds of conglomerates and sandstones, with shales and limestones, it is evident that the seat of deposition must be near the coast-line, either of the land on which continental deposits may form, or of the sea-bottom which receives sediments. Since, however, the whole accumulated mass of strata may be 20,000 feet in thickness, or even more, this must mean that subsidence of the marginal region of deposits took place as the sediments accumulated, for depths of this nature are not found already existing next to the land. The preliminary structure, then, which determines the place of the future range, is a subsiding trough into which sediments are deposited from a neighboring land, or lands undergoing erosion, until a great thickness has accumulated. This relation between subsidence and deposit of sediments has been previously discussed, page 239, and it has also been stated that an elongated subsiding tract of this nature is known as a *geosyncline*, page 305.

In the Appalachians the strata show by their fossils, markings and structures, such as have been described under sedimentary rocks, and by occasional beds of coal, as well as by the coarseness and characters of the sediments in repeated beds, that the deposition took place in shallow water, and was partly marine and partly continental in nature, and also that the process of subsidence was not a steady gradual one, but interrupted, with periods of upbuilding to land surface and of low uplifts, producing various configurations of land, swamp, and shallow sea. The history of these changes is fully discussed in the second part of this work. That the sediments are continued westward toward the Mississippi and beyond, growing finer, sandstones giving place more and more to shales, and limestones becoming more abundant, proves that the seas and water bodies lay in this direction, since the land deposits tend to give way to those more characteristic of marine origin. It follows as a necessary deduction, that, as stated above, there must have been a land whose erosion was furnishing the sediments and this land, to which the name Appalachia has been given, lay to the eastward of the subsiding trough. There were also other land areas to the northward and westward of the great embayment. Since Appalachia was a land, and being eroded, it could

not at that time receive sedimentary deposits, except local ones of a continental nature, and accordingly, we find no marine deposits of this geological age upon it between the eastern edge of the Appalachians and the Atlantic. In the adjoining plan, Fig. 282, is given the generalized outline of the geosyncline which received the heavy deposits forming later the Appalachians from southern New York to Georgia. The process here outlined continued until

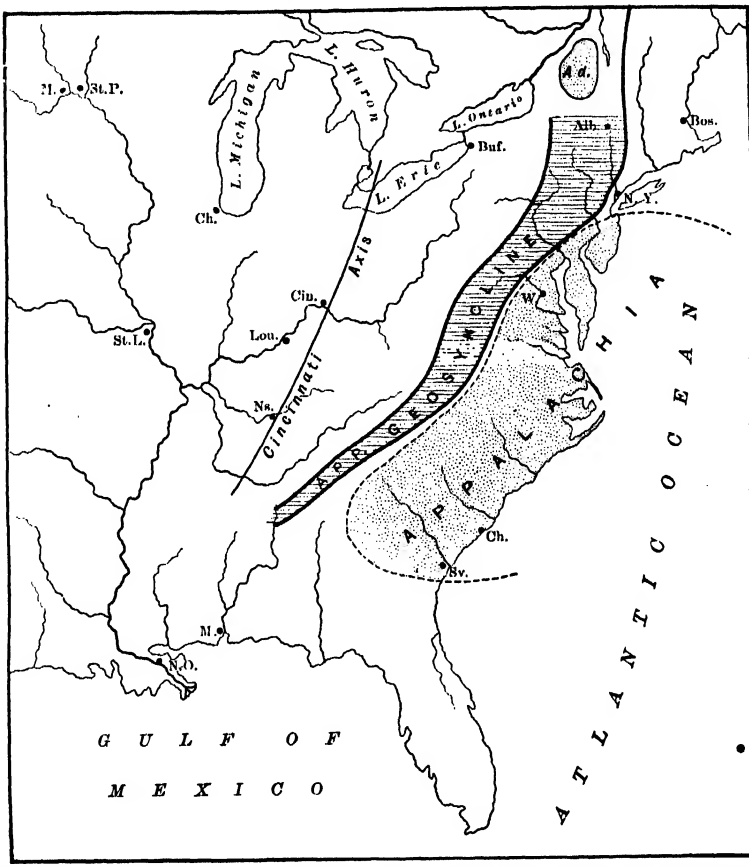


Fig. 282. — Map showing the situation of the Appalachian geosyncline and of the old land of Appalachia. *Ad*, mass of the Adirondacks.

the closing of the coal-making period of western Pennsylvania and until the 25,000 feet of sediments had been deposited, when the orogenic one commenced. It should be noted also that during the depression of the geosyncline, mountain-making forces were active over the western part of Appalachia, which was then in the condition of a rising geanticline. It was the reduction of these mountains by erosion that furnished much of the material that filled the westward lying geosyncline.

Similar processes have preceded the making of others of the great ranges,

both folded and complex. The Sierra presents the marginal deposits of a land that lay to the eastward where the Great Basin is now situated. After the mountains were formed, their erosion produced the material now seen in the Coast Range, so that here the mountain-making was successively transferred westward toward the Pacific. In the Alps the lands lay to the northward and their sediments were deposited in the sea to the southwestward, while in the Caucasus the old lands were to the southward and the sediments were laid down in seas stretching northward over Russia. It may be thus accepted as a general principle that on one side or the other of the folded ranges lies an area of much older rocks representing the source of the material which composes them, and upon which, therefore, marine deposits of that period are wanting. It may be that the old lands have been afterwards depressed and covered by still later deposits which mask them, but they must still be there.

Orogenic Period and the Forces Involved

The period of relatively quiet preparation which has been discussed, of long-continued erosion and sedimentation and slow changes of level of land surface and sea-bottom, gives way to a more active one in which the earth's outer shell yields to pressure which displays itself by enormous thrusting in a lateral direction,

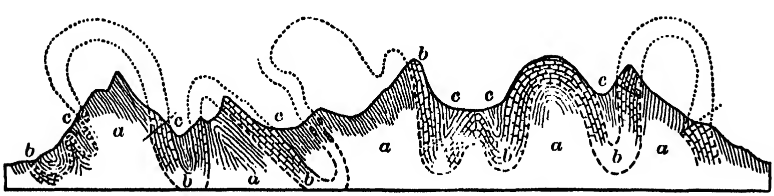


Fig. 283. — Section across the Säntis Alps, N. E. Switzerland (after Heim, somewhat modified). *a*, shales, breccias, etc.; *b*, massive limestone; *c*, shales, thin limestones, etc.

tangential to the earth surface. By this thrusting the accumulated load of sediments is thrown into folds, crushed and mashed together, so that the thickened mass rises and the mountain range is made. This constitutes the orogenic period. The process and its results thus simply stated are in reality very complicated, with different phases and with divergent features in different regions, some of the more important of which demand separate consideration. We shall take up first the operating forces and then the results produced.

Evidences of Lateral Pressure. — That the ranges have been made by the crushing together of the geosyncline with its burden of sediments by forces acting in a lateral or tangential direction is clearly evident by the structures which they present. Thus, in the

zone of most intensive folding, the folds not only become closed so that their limbs are in contact (see page 304), but they are even more severely compressed, with mashing of the beds, and the production of very complicated structures. This is shown in the adjoining section through a portion of the Alps, Fig. 283. It would

Fig. 284. — Layers of wax and plaster folded by lateral pressure, imitating structures found in folded mountain ranges. The thrust is from the right and in successive layers, from *a* to *e* the amount of shortening can be seen. Willis, U. S. Geol. Surv.

be impossible to imagine the formation of such structures except by transverse compression with relief by upward movement.

Experimental Proof. — Again the varied phenomena of folding shown in the mountains may be imitated by lateral compression of a sequence of artificial strata composed of layers of some plastic substance, such as wax or clay, placed upon one another. If these are laid in a firm trough or box, one end of which may be forced inward by the turning of a screw, structures are produced whose

character is shown in Fig. 284. The displacements and dislocation, the folding and faulting of the strata, produced in miniature by this method, are similar to those observed on a great scale in the mountain ranges.

Cleavage. — In the discussion of metamorphic rocks (page 342) it was shown that this feature of rocks, especially of slates, was due to great pressure, and that the planes of cleavage were perpendicular to the direction of pressure. Now the rocks of the great ranges in the zone of intensive folding are not only apt to be metamorphic, but also to show cleavage, being turned into schists and slates according to their particular composition. This becomes more evident as the inner portions of the compressed masses are exposed by erosion. Observation shows that the planes of cleavage usually stand at high angles, and are not infrequently perpendicular, while the strike of the cleavage planes is, in general, more or less parallel to the axis of the range. The direction of the compressive force, thus indicated by the cleavage, is the same as that shown by the folding.

Faulting. — It is obvious that such extreme folding as occurs could not take place without frequent rupturing, breaking and displacement of the strata, and consequent faulting. We find, therefore, that the phenomenon of faulting is very common in mountain ranges; both normal and reverse faulting being found. And as we pass from consideration of the simpler folded ranges to those of more complex types the faulting becomes more pronounced until finally, as we shall see later, it culminates in the production of thrust-faults of enormous magnitude. The small angle of incidence of the thrust-planes to the horizontal and their trends parallel to the axes of the ranges are indicative of the lateral compression, or approximately horizontal thrusting, which has produced them.

In summation then, we may accept it as a well-grounded fact that the folded ranges have been made by the lateral shoving, or squeezing together, of the stratified beds laid down in geosynclines. See Fig. 285.

The diagram Fig. 285 represents the general case in mountain-making in which land and sea continue to occupy the same position relative to one another. Applied to the Appalachians, however, one should remember that the sea in *A* and *B* is the interior sea which covered the Central States and was *west* of the land, whereas in *C* it is the Atlantic, *east* of the land. In *A* and *B* one is looking *south*, in *C*, looking *north*.

Amount of Compression. — No better idea of the magnitude of the forces involved, and of the masses operated upon, can be had

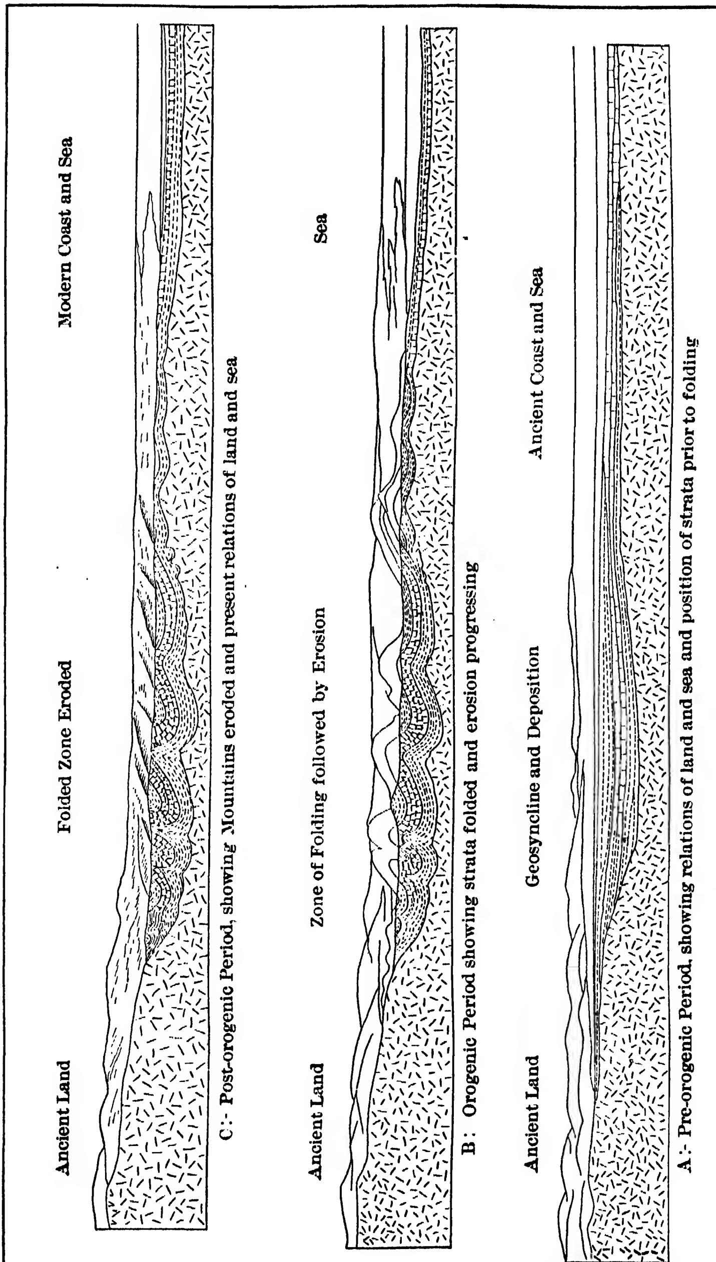


Fig. 285. — Diagram illustrating the origin and history of a folded range, such as the Appalachians. Modified from Willis, U. S. Geol. Surv.

than in considering the amount of compression which investigation shows has actually occurred in the making of some of the great ranges. In the Appalachians, estimates of 40 to 50 miles, and in some places even more, are given for the distances the original width of the strata in the geosyncline has been shortened by the mashing together of the mass. If some of the more extreme estimates are correct, the folded strata in Pennsylvania, if smoothed out like a crumpled blanket, would also cover a considerable portion of Ohio. In the eastern Rocky Mountains in British Columbia, McConnell estimates an original width of 50 miles has been shortened by compression into one of 25. For the Coast Range in California the shortening is about 10 miles according to LeConte's data. Thus in the production of the great folded ranges the breadth of the geosynclines has been diminished from 10 to 50 miles, or even more, and in the zones of intensive folding and mashing the reduction has been one half or more. If the original strata were 20,000 feet thick at these points, and, as used to be considered the case, the folds were upright, the compressed material would be double this in thickness, and the height of the mountains, disregarding the counteracting erosion, would be enormous. Actually, however, since the folds are mostly overturned, and even recumbent, the increase of thickness—and height—though considerable, must be much less than such an amount.

Influence of the Positive Elements and Direction of Thrust. — The old upland along whose margin the sediments have been deposited forms a positive element, or horst, in the architecture of the outer shell. It tends to rise as the geosyncline tends to sink, and as it becomes eroded the stronger massive rocks, igneous and metamorphic, of which its lower levels are composed, tend to rise toward the surface. It thus becomes steadily more massive and resistant, a more unyielding block or element in the shell. The sinking zone of accumulating sediment is one of weakness; whether the sinking is the cause for the accumulation of the sediments, or the result of it, has been previously discussed. Finally, when the shell yields to compression, the sediments are driven against this more resistant mass and are crumpled up. The result is that the beds appear to be carried against the previous continental area, or areas, by a thrust coming from the direction of the sea. It seems probable that this is largely apparent, due to the greater resistance of the horst, and that the contraction is general, so that the geosyncline is not only narrowed, but also shortened. Thus the general trend of the mountain chains seems to be determined by the situation of the old

lands which form the positive elements, or resisting buttresses, at the time the chains are formed, and the folded ranges may, therefore, be said to roughly outline ancient sea-coasts.

Thus the Appalachians from southern New York to Alabama indicate the former marginal coast-line of the old continent of Appalachia. It is believed that this is true, not only of the simple folded ranges, but of the more complex as well, in great measure, so that the trend of the Alps has been determined by old land masses, parts of which are now visible in central France, the Vosges, the Black Forest and Bohemia, and this relation is indicated on the outline map, Fig. 286.

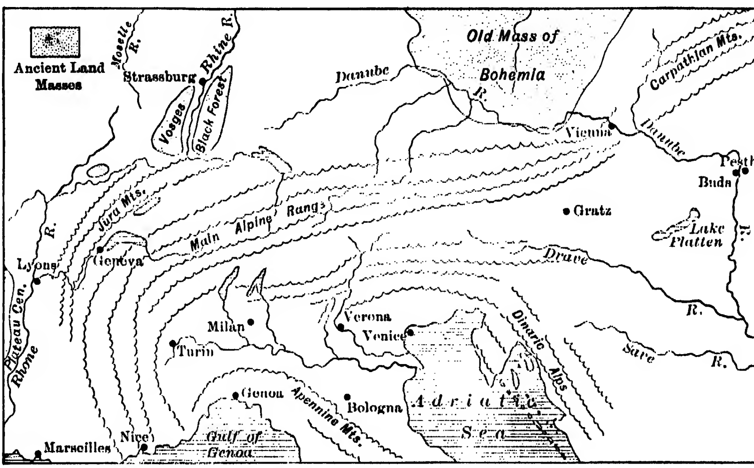


Fig. 286. — Showing the trend of the Alps and their relation to the old land masses.

The same relations are seen in other ranges, like the Coast Range of California, or the range of the Caucasus between the Black and Caspian seas, where the sediments laid out on the land margin and on the sea-bottom, the latter now represented by the level plains of Russia, were driven against the old land of Armenia, from which they were derived.

The direction in which the thrust appears to come, whether from the land toward the sea, or the reverse, for different ranges, has not been agreed upon by geologists. Thus Suess thinks that the thrust has spread outward from old land masses toward the sea basins, producing in the east of Asia the arc-like ranges, which, especially as islands on its continental shelf, fringe the coast-line. Others think the thrusts were, on the contrary, against this ancient land, called Angara. James Geikie thinks that across the North Pacific the thrusts were toward the east; in Asia toward the sea, in Western America toward the land. It has been customary to infer that the direction of thrusting is always shown by the attitude of the folds developed, that they tend to lean over in the direction to which the thrust is pushing them; that is, to be overfolds rather than underfolds; thus in Fig. 232 the thrust is from left to right. But, as Chamberlin remarks, this is a criterion of doubtful value, for the original attitude of the beds, and the nature of the thrusts, have much

to do with the character of the folding. As the negative, or depressed, segments of the earth's shell tend to sink more and faster than the positive segments, or horsts, see page 242, their borders are crowded against the latter. The horsts, being stiffer, resist and push back, and thrust is met by counter thrust. The part that is weakest yields and buckles up, or is shoved over the other. The direction of thrust is thus apparently much more one way than it really is.

Examples of Folded Range Structure. — It is evident from the preceding discussion of folded ranges, dependent upon the folding and, to some extent, the fracturing, that varied types of structure

Fig. 287. — Section *SE* and *NW* across the Jura Range, showing simple structure and symmetrical folding.

may be found in them, some of which may be comparatively simple, while others may be extremely complicated in nature. Some of these have already been described and illustrated by sections, but a few other important instances may be mentioned. Thus in some cases the structure is very simple and the ranges are composed of stratified beds only, thrown into more or less regular anticlinal and synclinal folds. The Jura Mountains of Switzerland, a western member of the Alpine system (see Fig. 286), have long been considered as a classic example of this, and a section through this range is given in Fig. 287.

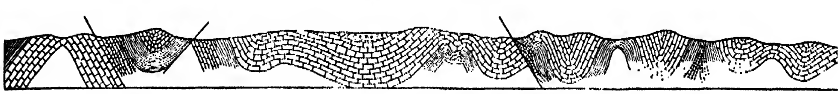


Fig. 288. — Section 12 miles long illustrating Appalachian structure near Greeneville, Tenn. Slightly modified from Keith and Willis.

The Appalachians from Pennsylvania southward present an example of a much more complexly folded range; in them folds of various kinds, closed, asymmetrical, and overturned, as well as faults and thrusts, are common. A portion of their structure is illustrated in Fig. 288. This complexity becomes so pronounced in many ranges, as in the Alps, by the overturning of folds and the successive driving of huge rock sheets over one another by thrust-faults, that we can no longer treat them conveniently in the same class with the simple folded ranges, but will consider them in a group by themselves, that of the complex ranges. It must not be understood, however, that the two groups are sharply separated in nature, for intermediate examples may be found. It is only for convenience and clearness of treatment that this is done.

Complex Mountain Ranges

In addition to simple folding, greater complexity may be introduced into the structure of mountain ranges by two other important factors. One of these is by the addition of igneous rock material coming from molten magma, either as intrusions, or extrusions, or both, and the other factor, as suggested above, is the occurrence of fracturing and thrust-faulting in places on such a scale as to greatly diminish the relative importance of mere folding. Of the three factors, folding, faulting (thrusting), and intrusion, the first has been sufficiently treated. We should now consider the other two.

Work of Igneous Agencies. — Although the making of mountain ranges by compression appears to be independent of direct igneous action, and in some cases there are long distances in them in which no igneous rocks occur, as in the Appalachian Range in Pennsyl-

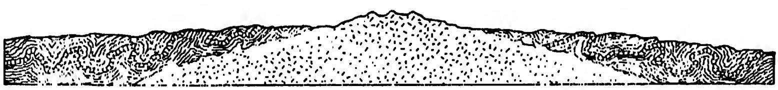


Fig. 289. — Illustrating the granite core of a mountain range as exposed after prolonged erosion. The strata on either side of the bathylith have become crumpled and metamorphic.

vania and West Virginia, and in the Coast Range in California and Oregon, it is nevertheless a very common thing to find that, attendant upon the folding, there has been an upwelling of magma from below, which is shown by the intrusions, or extrusions, of molten rock, and often of both, which are so frequently found in many ranges. The effect of this is to greatly add to the height and size of the uplifted mass, and to thus increase the volume of the range. Probably the most effective way in which this happens is in the intrusion of great bathyliths (see page 319), which are usually composed of granite, into the inner, lower portion of the range. A granite intrusion of this nature only becomes exposed later by deep erosion, and is then often spoken of as the "granite core" of the range. As a result of the intrusion, combined with the folding and mashing of the strata, the latter are subjected to profound metamorphic effects, and may be changed over wide areas to gneisses and schists, such as have been described in Chapter XIII. Instances of this are seen in some of the ranges of the Rocky Mountains' chain, in the northern Coast Range, in the Alps, the Caucasus, and others that might be mentioned, Fig. 289. The older a range is, the more deeply it will be eroded, and the more likely we are to find its rocks harder, more resistant, and the unaltered stratified

kinds to be replaced by metamorphic and igneous ones. The uprising of these great domed surfaces of granitic rock also generally adds to the elevation by carrying up the stratified beds upon them. We shall have occasion to consider this later when the results of erosion are discussed.

Invading granitic masses of this character are a marked feature of many mountainous tracts, such as those of eastern Canada, of New England (in the Green and White mountains), in North Carolina, and in the Sierra Nevada, for example, while the Alps, and the Caucasus, as well as the mountains of Scotland and Norway, can be mentioned as examples for Europe.

Where intrusions of molten magmas have occurred they may not only make great bathyliths, but pressing upward where relief is found in places and belts of weakness caused by folding, fractures, and dislocations, they may form intrusive sheets, laccoliths, chonoliths, plugs and stocks, or bosses. Or,

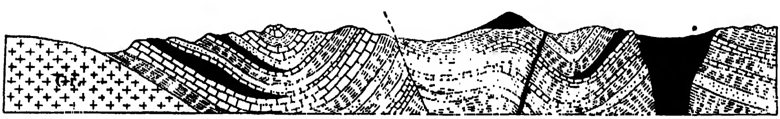


Fig. 290. — Section illustrating intrusions of igneous rock (black) in a folded and dislocated mountain region. *Gr*, edge of a granite bathylith.

attaining the surface, they may extrude as lava flows, often of great extent, and, if the physical conditions are right, give rise to volcanic action with the production of cones of large volume composed of tuffs and breccias. The Rocky Mountains in Colorado, Wyoming, and Montana are a striking example of this, and during the orogenic period were the scene of great volcanic activity which became especially pronounced toward its close, when many groups of active volcanoes existed. This igneous phase lasted long into the post-orogenic period and its dying remnants are still seen in the Yellowstone Park. As a result of the folding and faulting of strata, and the intrusion and extrusion of magmas, there were produced ranges with geologic structures of wonderful complexity, which are now revealed to us by the great dissection due to long erosion. The same features in greater or lesser degree are true of many other mountain ranges, and they are illustrated in Fig. 290.

Thrust-Faulting; the Alps. — Under the subject of faulting it was stated, page 366, that reverse faults occurred in mountain regions in a number of cases on a tremendous scale and with a fault surface of very low inclination, sometimes nearly horizontal. An illustration was given in Fig. 276. Such faults are known as thrust-faults, or, more simply, thrusts. It is now proper to consider them in their relation to mountain making. We can do this perhaps best by the study of a particular case, that of the Alps.

According to the Swiss and French geologists, who have made detailed investigations of the Alps, the history of this great mountain

system may be summarized as follows. It begins with the gradual submergence of an ancient land covering the region of the modern Alps. This old land had, without doubt, been itself a mountainous tract, but long continued erosion had mostly worn the elevations away, and reduced it to a low country. It was then composed mainly of crystalline rocks, igneous and metamorphic, with some included strata. As it sank, it was covered by a series of deposited

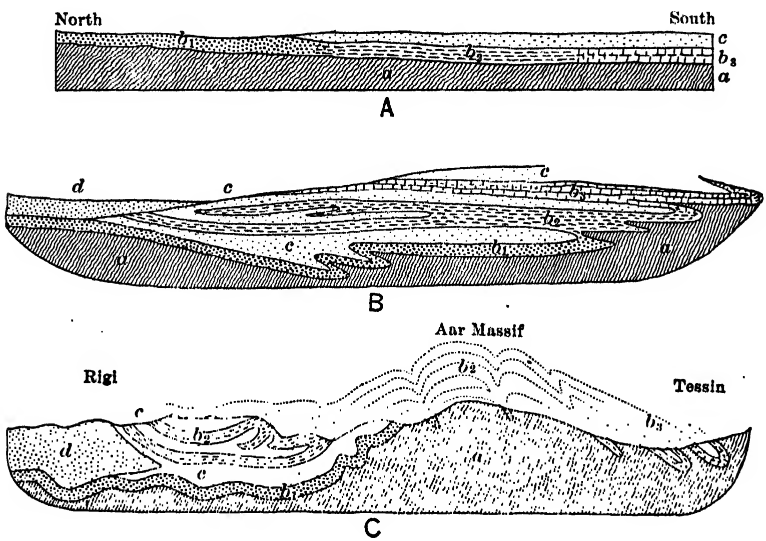


Fig. 291. — Diagram illustrating three phases in the history of the Alps. *A*, pre-orogenic period: *a*, crystalline basement rocks; b_1 b_2 b_3, deposited strata (Mesozoic) in three varieties (facies); *c*, younger strata (Oligocene).
B, after the first orogenic movement: successive rock sheets thrust northward are seen overlapping; *d*, conglomerate (Miocene) resting on eroded older formations.
C, after the second orogenic movement and great erosion: Alps of the present.
Each section is shorter through compression and represents only a part of the one above it. After Steinmann, slightly modified.

beds, the waste of lands to the northward, shales and sandstones, associated with limestones of marine origin. These strata attained a thickness in places of 10,000 to 15,000 feet. This was the pre-orogenic period.

The orogenic period begins with compression of the area in a general north-south direction, generating a thrust that apparently was directed toward the north. Seemingly, this did not seriously affect the crystalline basement rocks, although, as suggested, they may have risen in a broad low dome, a geanticline. But the super-

imposed strata were thrown into folds, and over wide areas these developed into overfolds which faulted, and the upper limbs were driven forward as huge rock sheets for vast distances over the thrust-surfaces. It is even thought that in some cases the strata broke and were forced forward without folding. Thus a great series of rock sheets were thrust northward, the later partly over the earlier, reversing in places the normal order in which they had been deposited. They covered up the earlier crystalline basement.

Then followed a period during which, if crustal movement did not absolutely cease, there was relative quiet, and the rock sheets rested. Their whole overthrust masses were subjected to profound erosion and in considerable part carried away. Especially along the north front of the Alpine mass this waste was deposited in enormous thicknesses of gravels, which formed in time heavy conglomerates. The deposits were laid down in an inland sea which covered an area to the north of the mass.

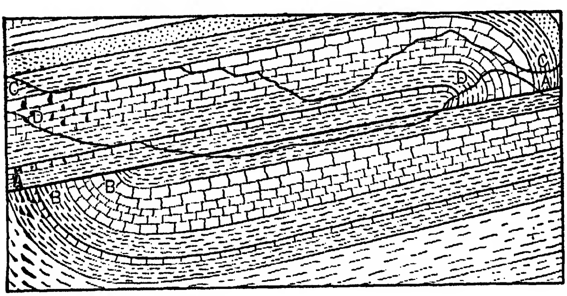


Fig. 292. — Movement of a broken recumbent fold along a thrust-plane *A,A*: above *A,A*, to the right; below, to the left. *B,B*, the "roots" of the fold left behind; *D,D*, and *C,C*, two possible surfaces of erosion.

Next followed a renewed period of compression and northward and northwest shoving. But this time, instead of the driving forward of rock sheets, the latter were thrown into folds and the underlying crystallines were also bulged up in great masses. In the movement the great conglomerates were driven against and disturbed and the outlying deposits folded up, as in the Jura Mountains. The final consequence was the forming of the east-west and north-south ranges of the Alpine system, as we now know them. See Fig. 286. The results of three phases of Alpine history may be seen in Fig. 291, diagrammatically depicted.

The process of thrusting briefly sketched above for the Alps, applies also in a general way for many other of the ranges. We know

that it has occurred in places in the Rocky Mountains, in the old mountains of Scotland and Norway, to some extent in the Appalachians, and elsewhere. The transference of the rock masses is to be measured, not only in miles, but in tens and scores of miles, even up to 100 or greater. Only as the careful and patient study of the great ranges goes on are we able to measure and appreciate its amount and significance.

The manner in which the thrusting is supposed to occur by the breakage of a fold may be illustrated in Fig. 292; if erosion should proceed to the line *D–D*, a mass like *A–D* at the right would consist of older formations resting upon younger ones and would be spoken of as a mountain without "roots." Chief Mountain in Montana, see Fig. 276, is an example of this, and there are many in Switzerland, like the Matterhorn.

It should be stated that some students of mountain structures do not entirely agree with the interpretation of Alpine history offered by the European geologists, and sketched above; it has however received general acceptance.

Origin of the Compressive Forces. — When it was believed that the earth consisted of a relatively thin crust resting on a highly-heated liquid interior it seemed easy to explain the origin of folded mountains by assuming that there was a regular contraction of the earth's mass from loss of heat, and, since this contraction was greater in the heated interior than in the cold outer crust, the latter was folded up as it gradually sank upon the shrinking core, very much as the skin wrinkles upon a drying and contracting apple. This view, for a variety of reasons which have been stated, we can no longer hold; the earth behaves like a relatively solid, rigid body; it cannot be wholly, or even largely, fluid within, in the ordinary meaning of the word, and, except locally or to a superficial depth, it may not be hot, at least in any such sense that it could experience the notable contraction from loss of heat demanded for the origin of the folded ranges.

The evidence, however, that these ranges have been formed by lateral compression, acting with tangential thrusting movement, is, as has been shown, direct and positive; we cannot conceive of forces acting in any other way which would yield such results. Since the contraction in a horizontal sense is evident, it is for us to find an explanation of it; is it due to contraction in a vertical sense, that is, radial contraction of the earth as a whole, or may it be explained in some other way? The volume of the earth is so vast, that, in considering this question, we are liable to become confused by the multiplicity of the processes which affect it, but by regarding smaller objects whose dimensions and properties we can hold more easily in

mind, the only way in which we can logically conceive of the surface of a spherical mass contracting is by a lessening of the volume of the object as a whole, and by simple analogy we must imagine this to be the case with the earth.

If, then, we are required to rely on contraction of mass as the ultimate cause for the contraction of surface area, which produces the lateral pressure, it is possible to conceive of this as occurring from different causes, either mechanical or chemical. They may be briefly discussed.

Mechanical Causes of Shrinkage. — Probably the view which is most commonly held to account for contraction is the loss of heat. This is the survival of the idea mentioned above as held when it was believed the earth was liquid within, but changed to accord more nearly with later knowledge. It supposes the earth to be solid and rigid but very hot within (see page 261) and by the progressive loss of this heat the shrinkage to be caused. We cannot say positively that this view is untrue, but if several essential facts be taken into account it seems improbable. These facts are as follows:

If we introduce quantitative elements, as first suggested by Dutton, it is clear that every mile of shortening of an arc of the world's surface requires a shortening of the diameter of $\frac{1}{3.1416}$ mile, since this is the relation of circumference to diameter, or in round numbers a shortening of the radius of one mile shortens the circumference six miles. To make the ranges now existent it used to be thought that a shortening of the radius from 20 to 40 miles at least from Cambrian time to the present was necessary to give the requisite contraction and surface reduction, but the more recent work of Heim and other geologists in the Alps and elsewhere shows that these figures must be greatly increased. Heim now thinks that the original Alpine area before folding was from 400 to 750 miles broad and that this has been reduced to 100 miles in the crushing together. The reduction for the loss of a given amount of heat has been calculated and the results prove that to accomplish the necessary shrinkage a very improbable loss of heat would have had to occur. Moreover, every explanation for the cause of the contraction that is offered must take into account two things: first, that both the paleontologic study of the life history of the earth, and other facts relating to the formation of the stratified rocks, show very clearly that essentially similar conditions of land and water, of atmosphere and climate, have obtained upon it for an immense period of geologic time, during which most of the great ranges we know have been erected; and second, that mountain-making has not been a regularly

progressive process, but a periodic one, occurring in cycles, interrupted by long periods of earth-rest, as we shall see more fully discussed in the second part of this work. The simple loss of heat alone does not explain this latter fact, nor can we believe that within the historic period of geology the outer shell of the earth differed essentially in its heat content from that of to-day. The possible cause for this thermal equilibrium appears to be of chemical origin and will be discussed in a following paragraph.

Of other mechanical causes suggested, one is the transfer of molten material from within to the surface, causing the outer shell by its own weight and that of the added material to tend to sink in, and thus to be under compressive strain. This is a real cause so far as it goes; but it does not go far. The extrusion of 1,000,000 cubic miles of lava would furnish but a small fraction of the shrinkage required for one of the great ranges.

Based on the theory of isostasy (see page 239), it is assumed by some, that, as the heavier segments of the earth sink, matter is crowded toward, and against, the rising positive segments, or horsts, and that this flowage produces superficially a wrinkling of the outer crust which gives rise to mountain ranges. The work of Barrell, however, although it shows that the mathematical evidence proves the existence of *regional* isostasy, just as clearly disproves the latter as a cause of folding. Other causes have been suggested, such as the transfer of heat from an inner core to an outer zone, but not necessarily to the actual surface whose temperature remains substantially constant. It has been considered that no unreasonable fall of temperature of the inner core would produce in the outer shell, which receives heat faster than it loses it from the surface, an expansion yielding the results demanded; this could not be, of course, a process continuing indefinitely, but, according to the view, is still in operation. Still another view suggests the condensation of matter toward the center, with a growing density of the mass, and a consequent lessening of its volume. Such views are, however, purely hypothetical and their correctness we are able neither to affirm nor deny. The last one, however, bears so closely on the chemical explanation given below that it seems a necessary consequence of it.

Chemical Cause of Shrinkage. — We have had occasion in several places to refer to the part which the chemical disintegration of matter may play in geologic processes. Some of the elements are known to decompose into others, in part gaseous ones. Thus uranium is held to decompose into products of which lead is one and helium, a gas, is another. With the escape of the volatile substances, some of which, like helium, would probably not be held by the earth but would pass off into space, there could be a condensation of volume. It may be that this property of matter is much more general than has been supposed, and occurs on a scale which would make it applicable to the present problem. But the process of such disintegration is attended by the production of a relatively enormous amount of heat, and if we imagine it as occurring on such a scale that it becomes the factor in the making of mountain ranges by contraction, we must also deal with the heat generated. We might be forced to consider the earth as growing hotter instead of cooler, whereas, from early geologic times, the outer shell appears to have

been in thermal equilibrium. But if elements can disintegrate, it may be that under proper conditions, such as might obtain in the centrosphere, they can combine, and heavier be made out of lighter. This would entail contraction of volume and, probably, *absorption* of heat. These views are, however, purely speculative. All we can safely say at present is that the geological evidence seems to indicate a progressive condensation of the centrosphere.

General Summary. — From the discussion given above as to the ultimate origin of orogenic forces, it is clear that at the present time we are not able to draw a definite conclusion, or one that would meet with general acceptance. It seems reasonably safe to say that they have been caused by contraction of the mass-volume of the earth, and that it is probable that this contraction is not a simple process, but due to a variety of causes whose complexity we are only beginning to appreciate. This is the more evident when we see that the orogenic process has not been a regularly progressive one but periodic and, perhaps, rhythmic, in its operation. If the outer shell were sufficiently rigid to withstand the contractive strain, we might understand this periodicity as the times of yielding to accumulated stress, but since we see this layer constantly yielding to it, with the production of faults, earthquakes, subsidences, etc., it is clear that it cannot be always yielding to stress and accumulating it at one and the same time. The cause of this periodicity is at present a mystery, which it may be hoped further scientific knowledge will unveil.

Origin of Block Mountains. — The folded ranges, as we have seen, are due to the crushing of thick deposits laid down in those broad, concave sinking tracts which have been termed geosynclines. The resultant crushed mass has been appropriately called a *synclinorium* by Dana, that is, mountains formed in a syncline. In a similar way we can imagine the earth's crust warped into broad upward folds, or domes, of relatively low uplift, to which the name of *geanticlines* has been given. If a dome of this character is relatively small it may be able to sustain itself, but if of very wide extent, several hundred miles broad, and thus corresponding to the great geosynclines in size, it may be unable to do so, and the arch may break down, with the production of normal faults and tilted blocks. Whether we regard such a movement as produced by contraction of the crust with inflowage of matter beneath it and consequent uprise, or as a rising of a positive element or horst (see page 242) according to the theory of isostasy, is largely a matter of definition, the result is the same. If the dome remains unbroken it forms a plateau which erosion may carve into mountains; if faulted

and broken, the results may be like those seen in the Great Basin and previously described.

The Black Hills of South Dakota, and on a smaller scale the Little Rocky Mountains of Montana, represent domed uplifts which have been competent to sustain themselves. The strata on each uplift need not necessarily be

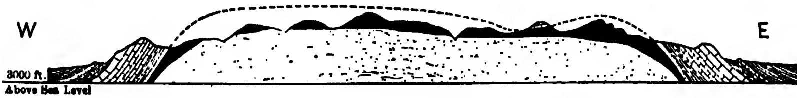


Fig. 293. — Section through the Little Rocky Mountains, Montana. Main dome of gneisses and schists. Black shows remnants of an intrusion of porphyry. At borders, upturned strata, remains of which still rest on the porphyry. Length of section about 10 miles.

thick, such as would accumulate in a sinking geosyncline, and in their cases have been largely removed by subsequent erosion, and are found as upturned ridges about the flanks of the dome, see Fig. 293. The rising of the arch tends to lower the local pressure and to be accompanied by inflow and, at all events, by upflow of material, which is marked by the intrusion of igneous magmas as stocks, dikes and sheets, and in areas of weakness and relief of pressure on the borders as laccoliths; these intrusions help to swell the volume of the uplift. Subsequent erosion carves the mass, whose general ground-plan is more or less elliptical or even circular, into a group of mountains and valleys.

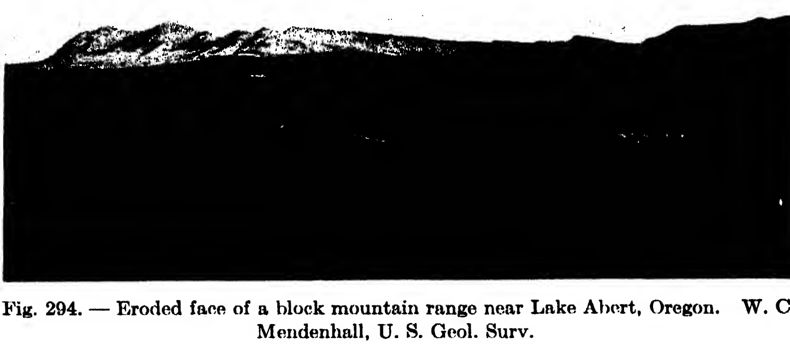


Fig. 294. — Eroded face of a block mountain range near Lake Abert, Oregon. W. C. Mendenhall, U. S. Geol. Surv.

In the case of the Great Basin, the arch, as generally supposed, has broken down, leaving the Sierra on one side and the Wasatch on the other as the former abutments; it seems to have been too vast to have been able to sustain itself, see Fig. 280, and the sunken blocks form ranges, as previously described, Fig. 294. It appears, however, quite possible, considering the vastness of the basin, that the arch, as such, never really existed, but that the blocks were formed during and after the uplift by differential support, and not by subsidence. Here, too, the same upwelling of magmas with intrusions and vast outflows of lava has occurred. This region has been considered

by some to have been subjected to great tension, or stretching, of the crust, with breaking down into block mountains by subsidence, but it is difficult to account for such an effect and it seems more reasonable to regard it, and similar tracts, as incomplete or broken-down geanticlines, thus bringing them into correlation with the general contractive movement of the earth, and with folded ranges. It is generally assumed that all of the major faults are normal in character, but more detailed study of the region may determine some of them to be reverse.

Geological Date of Mountain-making. — The geological period at which a geosyncline has been crushed, and the strata compressed into a mountain range, is determined by observation of the age of the latest strata involved in the folding, and of the oldest beds rest-

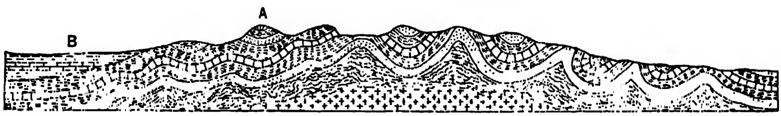


Fig. 295. — Illustrating determination of the date at which mountain-making occurs. *A* are the youngest strata involved in the folding; the folding is younger than these; *B* are not concerned in the process and are later; the folding is older than they are.

ing undisturbed by mountain-making processes upon the disturbed rocks about the mountain flanks. The date of folding is obviously younger than the folded or disturbed beds and older than the undisturbed ones. This will be clear from an inspection of Fig. 295. The accuracy of the method evidently depends upon the shortness of the interval between the times of deposition of the two sets of strata *A* and *B* in the diagram.

The process thus briefly stated is the general one for the solution of the problem, but it is apt to be more complicated than as given above. If, as is so often the case, the mountains have been formed, not in one, but in several periods of compression, it can refer only to the latest. Moreover, erosion may have entirely carried away the younger disturbed strata from their exposures in the mountains, leaving a greater blank between *A* and *B*. Thus the older, and in consequence, the more eroded the mountains are, the more uncertain becomes the time of their formation.

Thus it has been determined that the Appalachians were formed for the most part during the Permian period, the Rocky Mountains at the close of the Cretaceous and, therefore, later; the Alps mainly at the close of the Miocene period and thus still later.

The Appalachians were long in making, the process lasting through several geologic periods. The first of the known thrusts came in the Lower Cambrian, the second towards the close of the Ordovician, then in the late Devo-

nian came another, still another near the close of the Mississippian and, finally, the culmination in the great thrust in Permian time.

Summary of Orogenic Period. — From what has been stated in the foregoing pages we see that the mountain ranges which have been formed by movements of the earth's shell may be due to several different processes, or to combinations of them. They may have been made by the simple dislocation and tilting of blocks, by folding without great faulting, or by large thrust movements, and in many cases by combinations of thrusting and folding. And along with these there are likely to be injections and extrusions of molten magma, which add their quota to the mountain masses. Thus while simple types of structure may be found, the great ranges, on the other hand, usually present very complex characters. Neither must we also overlook the fact that many of these ranges have existed for long periods of geologic time during which they have experienced at intervals powerful compression and thrusting, as already mentioned for the Alps and the Appalachians. Such times of orogenic pressures are intermitted by periods of rest during which the mountains may suffer great erosion. This gives rise to the geological cycles treated in a following section. We are thus led naturally to consider what happens to mountains when the orogenic forces cease operation.

Post-Orogenic Processes

Although we may classify mountains by the structural processes which have aided in their formation, it is not to these processes alone that the mountains as we now see them are due. For the uplift of a dome, for example, like that of the Black Hills, would of itself furnish us only with a plateau, not necessarily with mountains. Hand in hand with the raising of the masses goes the work of erosion, that mighty chisel of Nature, which shapes and carves them into the mountain forms familiar to us. And as by simple differential erosion we see projecting buttes and rock spires left as remnants, so it is conceivable to us that this process alone, aided by underlying structure, might, from a relatively level country, etch out forms whose magnitude would compel us to call them mountains. The residual mountain blocks situated in the trough of the Grand Canyon are an example of this, as previously stated.

The work of erosion, then, is of the greatest importance in a full consideration of mountains, it begins with the first rising of the masses, proceeds while the orogenic forces are at work, and con-

tinues long after they have come to rest. As its results become especially marked in this last stage, it must be considered the chief agent in mountain-making in the post-orogenic period, and some of its more important results may now be considered.

Earlier Stages of Erosion. — So long as the compressive orogenic forces are at work, a mountain range will be growing, in so far as its structure is concerned. Whether it will be actually rising in height, or not, depends on the adjustment of the varied forces at work upon it, the lateral pressure, for example, in a folded range which tends to make it rise, and the work of erosion which tries to cut it down. Always, during this formative period, there is this struggle going on, and the range as it exists at any time is the resultant between the two. When the orogenic movements cease, then denudation has full sway and, ultimately, with the lapse of sufficient time and provided no renewal takes place, the range must be cut down, base-leveled, and extinguished by the ever-gnawing erosion. In this process various stages are to be distinguished. When the range is at its maximum of elevation then the erosive agencies are most severe; to the work of running water on steep slopes is added very commonly the effect of frost, snow and ice. It may happen also at this time that the rock material exposed to erosion consists of the later beds laid down in the geosyncline, which have suffered less metamorphism than the deeper, older ones, and are thus softer, or less resistant, to erosive attack. If igneous injections and extrusions have contributed to swell the volume of the range, it will also be the more easily eroded tuffs and lavas that are first exposed. Hence, in general, the outer material is more easily cut away, and with progressive erosion the inner core becomes more and more resistant. Thus, in the early history of a range not only is the severity of attack of eroding forces apt to be increased by greater height, but they may find less resistant material to work upon. At first the upraised masses begin to be cut by the valleys of the necessarily consequent streams. The drainages thus appear upon original slopes and continue to work downward and backward into the range. As they do so they begin to be conditioned more and more by the structures and nature of the underlying rocks. From such a youthful stage, as time goes on, the masses become profoundly graved and rugged, characterized by peaks and towering rock pinnacles, which alternate with deeply scored valleys. The strongly notched outline of such a range at a distance presents a saw-toothed appearance, which has led to the Spanish name of Sierra, a saw, being given to them. The topographic development of the range thus proceeds

from youth into early maturity, and as erosion continues and the valleys widen, the declivities lessen, angularities of form tend to disappear, and it becomes more and more mature. The topographic forms of the peaks and ridges and of the intervening valleys must obviously depend largely on the nature and structure of the rock masses presented to erosion. A discussion of them would carry us too far, but some important features are described later.

The Jura Mountains of Switzerland, see Fig. 287, present a type of somewhat youthful dissection; here the structure forms produced by folding still cause the dominant topographic features, which erosion has, as yet, been unable to essentially modify. Ranges like the Alps, the Himalayas, the Caucasus and many of our Rocky Mountains' system, are in mature stages of dissection, although their topographic relief, that is, their mountain forms and valleys, is dominantly one of erosion, and evidently not of folding, as in the Jura. The words youthful and mature in this connection must be understood to be merely relative terms and not ones of absolute time; actually one range may be much older than another and yet, on account of its greater mass, difference in material, or situation as to climatic severity of erosion, be in a younger stage of dissection. This has been previously explained with respect to river valleys, page 51, and is equally true here.

Fig. 296. — Illustrating characteristic forms and outlines of late mature mountains.

Later Stages of Erosion. — If erosive processes continue their work of degrading a mountain mass, unhampered by further upward growth from orogenic agencies, the range gradually passes into a *mature* stage. As stated above, the sharp peaks and roughnesses tend to disappear, the valleys to widen and open. And as the work continues it goes more slowly as the inclination of slopes lessens, and as, in most cases, the most resistant metamorphic and crystalline igneous rocks of the inner core, or axis, are reached. Thus in a range, very maturely dissected, we are apt to see gently modeled, rather smoothly rounded forms and outlines, as suggested in Fig. 296, which contrast sharply with the angular features of the Sierra type. And, as they wear down more and more and pass gradually into old age, we are apt, as stated, to find these mountains composed of massive rocks, of schists, gneisses, granites, etc., rather than of the limestones, sandstones, shales and lavas, of ranges in the earlier stages.

There appears to be no well-recognized term for mountains in these later stages equivalent to Sierra; they are variously termed mature, subdued, or old mountains. Examples of them are to be seen in the mountain groups

and ranges of New England and eastern Canada, such as the Green Mountains, the White Mountains, and the Laurentides of Quebec, while in Europe the Black Forest region in Baden, and the old mountains of Scotland and Norway are illustrative of them.

Final Stage: Peneplanation. — Ultimately, provided that no new upwarping movements occur, the mountains will disappear and the region which they occupied will be nearly reduced to base-level. See page 70. Since, however, the process of erosion goes on more

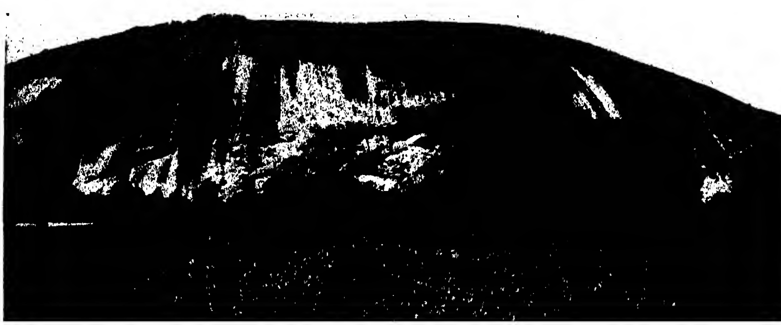


Fig. 297. — Stone Mountain, De Kalb Co., Georgia. A monadnock, consisting of granite, which rises above the surrounding plain of erosion. T. L. Watson, Geol. Surv. of Georgia.

and more slowly as the slopes lessen, it would evidently require an enormous lapse of time to actually bring down nearly to base-level a mountainous tract, and we have no proof that this has ever actually occurred. But we know in some cases such areas have been reduced to a relatively low, almost featureless country; in other words to a *peneplain*. Such a country may still be diversified by an occasional hill projecting above the general level, a residual of erosion, which, on account of the more resistant nature of the rock composing it, or possibly its originally greater size, has not been reduced like its neighbors. Such elevations, projecting above the surface of a peneplain, have been termed *monadnocks*, from Mount Monadnock in New Hampshire, which rises above the peneplain upland of central New England. An example is seen in Fig. 297.

Disregarding occasional monadnocks, we may say that when the peneplain stage is reached the mountains have been obliterated, but

we may yet be able to recognize the fact of their former presence by the upturned and dislocated nature of the transversely eroded strata, by their frequent metamorphic condition, by the slaty cleavage and faults which they exhibit, and by the frequent presence of stocks and bathyliths of granitic rocks intruded into them. We may not find the elevations, for, as LeConte has well said, "we find only the bones of the extinct mountains," but from these remains we may be able, in imagination, to reconstruct them. So, from the conditions of the rocks of southern New England, which is now only a hilly country, we are led to infer that it once presented the aspect of a mountainous region with lofty ranges running through it, north and south.

Re-elevation: the Geological Cycle. — From what has been said in the foregoing pages it will be clear that the life history of mountain ranges is not necessarily a simple one consisting of a single period of compression, uplift, denudation, and extinction. On the contrary, the more they are studied the more evident it becomes that their history, in most cases, is much more complicated, and that the compressive orogenic forces have acted spasmodically, with repeated times of uplift. When a much eroded range is again elevated, it may be said, as with rivers, see page 72, to be rejuvenated; the erosive agents must again set to work on their task of cutting it down. Thus a single period of uplift, and then of down-cutting by erosion, may be considered a geological cycle, and examination shows that some ranges have passed through several such cycles. The Appalachians are an example which has been thoroughly studied. Originally they were formed, as has been stated, during the Permian period. They were then doubtless lofty mountains, but in succeeding time they were so greatly eroded that in the Cretaceous period the tract had been reduced to a peneplain, with only here and there occasional monadnocks rising above it. After this its surface was again domed by repeated upswellings and the revived rivers have carved it into its present condition.

It must therefore be remembered that when we speak of mountains being young, mature or old, with reference to their present topographic development by erosion, it is with the present cycle of uplift that we are dealing. Thus a range may be young in topography by rejuvenation but old geologically, and composed of ancient rocks. This has been previously pointed out in the Alps, and it may be suspected that many ranges, like some of the Rocky Mountains' system, which we regard as young or mature have really been rejuvenated from old age.

It is through a recognition of such repeated cycles of rejuvenation and erosion that we are able to understand the problems presented by the topog-

raphy and drainage of many regions. For example, we see that master streams have been able to maintain their courses during the time of re-elevation and have sawed their channels regardless of the underlying rock structure, so that they are now cutting through ridges and across the strike of the strata over hard and soft beds alike, instead of having their courses determined along weak belts as we should naturally expect, see page 76.

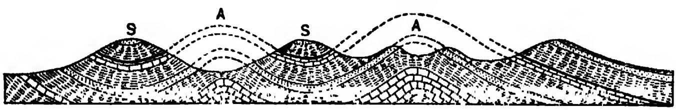


Fig. 298. — Illustrating anticlinal valleys and synclinal ridges.

Plateau-forming Movements. — In connection with what has been said in the preceding paragraph it may be well in concluding the section on mountains, to again bring to attention the importance of great plateau-forming movements, described on pages 375-377,

Fig. 299. — Erosion of folded strata. North Beaver Creek, Bighorn Mountains, Wyo. N. H. Darton, U. S. Geol. Surv.

as a factor in terrestrial relief. In contrast with mountain ranges these relief features have been produced by vertical movements, and to them the largest irregularities of the surface are due. In most regions marked uplift has taken place later than folding, even when the latter is of recent geological age (Miocene or Pliocene).

Some Results of Erosion in Folded Strata

Anticlines and Synclines. — The result of the erosion of mountain ranges, which commonly contain a variety of stratified rocks, folded and dislocated in different ways, and often igneous ones

as well, is the production of many kinds of topographic forms, dependent on the attitude of the beds and on the relative hardness, or resistance to erosion, which they exhibit. Although some of these forms may be seen in regions of low relief, they are, as a rule, best studied as a phase in the history of mountain-making. One example is found in the erosion of anticlines and synclines. It would be natural to think that in a folded tract the anticlines would be ridges and the synclines valleys, and in young ranges this may, indeed, be the case, as in the Jura Mountains. But when maturely dissected ranges, such as the Appalachians, are studied it is very commonly found that, on the contrary, the valleys are cut in the crests of anticlines, whereas the ridges are the bottoms of

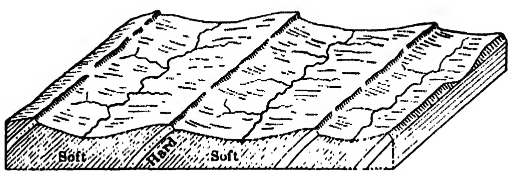


Fig. 300. — Illustrating the formation of longitudinal valleys of erosion and parallel ridges.

synclines. In other words, the original topography, with respect to the structure, has been reversed. See Fig. 298. The student must, therefore, remember that anticlines and synclines are terms of *structure*, that, as previously explained, they do not necessarily denote forms of topographic relief.

The reason for this appears to consist primarily in that an anticline's crest, when in formation, tends to be under tension, that is, to be stretched; consequently, the strata are apt to be thinned and cracked, producing a belt of weakness. The bottom of a syncline, on the contrary, is under compression, joints and cracks become closed, and being thus strengthened, it can resist erosion better than the anticline. In the general lowering of the country by denudation the streams tend to carry away the anticlines faster, to seek out the weak belts, and to establish their valleys in them. See Fig. 298. If the beds consist of alternately hard and soft strata the effect will be more marked, because the hard stratum will be cut through first on the crest of the anticline, where it is highest and most exposed; the softer material below being reached, the erosion in it will be more pronounced than elsewhere. Thus, both by position and structure, the anticlines tend first to be worn away, and then to become valleys.

After the Appalachians had been reduced to the Cretaceous peneplain and then rejuvenated by doming, it was chiefly along belts of weak rocks in the anticlines that the subsequent streams established their valleys, Fig. 288. In a few cases where a hard resisting stratum has emerged through erosion anticlinal ridges have been formed.

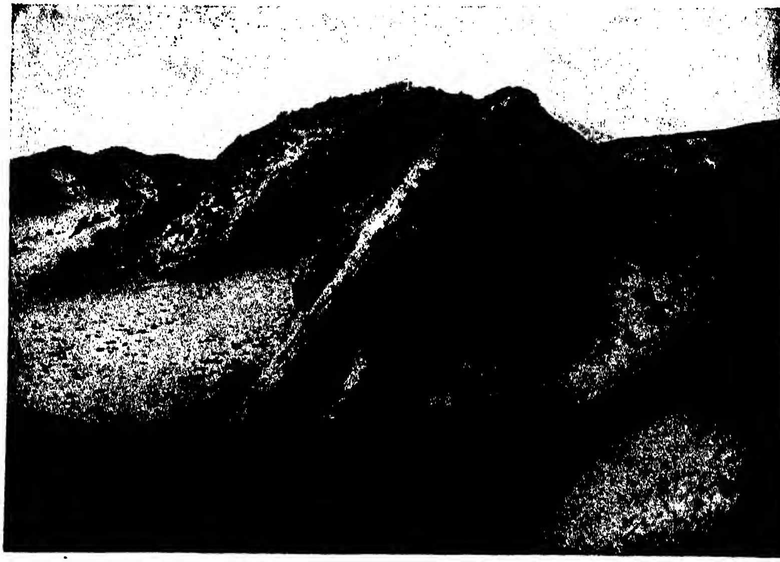


Fig. 301. — A hogback, near Gallup, New Mexico. N. H. Darton, U. S. Geol. Surv.

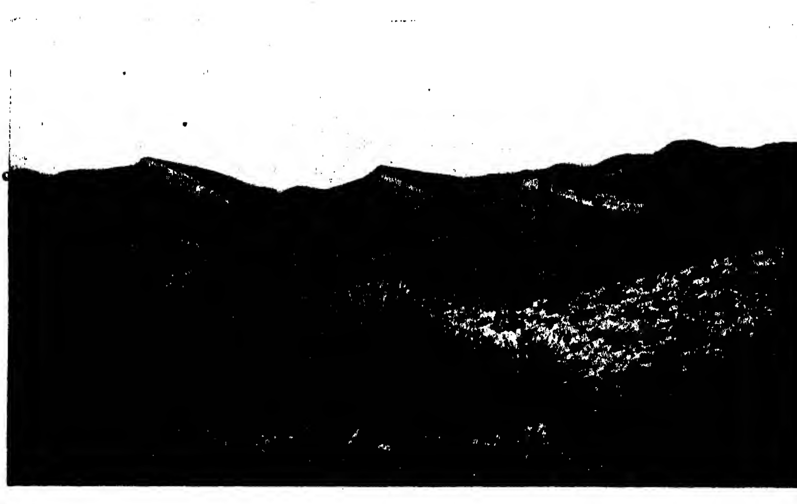


Fig. 302. — View illustrating the development of topographic forms and drainage in inclined beds of hard and soft strata. Near Bisbee, Ariz. F. L. Ransome, U. S. Geol. Surv.

Parallel Ridges: Hogbacks. — As the erosion of folded strata composed of hard and soft beds proceeds, and the hard beds are broken through on the anticlines, drainage ways tend to establish themselves along the belts of weak strata, as noted above. This gives rise to *longitudinal* valleys, following the strike of the beds, while the outcropping edges of the hard strata form the crests of the intervening ridges, as illustrated in Fig. 300, where several such valleys on the side of an eroded anticline have been made. Parallel ridges of this nature are a characteristic feature over much of the eroded Appalachian mountain tract and are found in many other districts of disturbed strata. In the foothills of the Rocky Mountains' region, where the level strata of the plains begin to show the initial foldings and displacements which culminate beyond in the ranges themselves, short eroded ridges or hills of this nature are very common, and are popularly known as *hogbacks*. They may be several hundred feet high. An illustration of one is seen in Fig. 301.

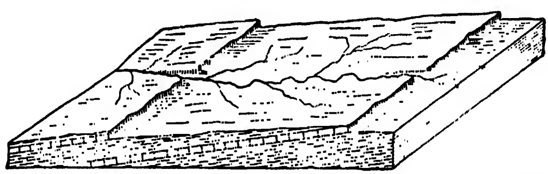


Fig. 303. — Diagram illustrating the formation of cuestas and escarpments.

In the erosion of a country with the structure seen in Fig. 300, the wear on the side of the valley which exposes the outcropping edge of the strata is more rapid than on the slope made of the backs of the beds. The whole system of drainage tends on this account to move in this direction, that is, to the left, in the figure. There is evidently, then, a shifting, or, as it is technically called, a *migration* of the divides between the valleys. If the structure is similar on both slopes of a divide, as for instance in horizontal beds of clay, then the erosion will be most rapid on the steeper slope, and the divide will migrate toward the gentler one, other conditions being equal. This movement of divides is constantly going on in a country undergoing erosion, its rapidity depending on the rate of the erosion, and in the struggle between divides new adjustments of drainage are constantly taking place. See Fig. 302, and also Fig. 21. This fact furnishes the key to the solution of problems regarding the origin of the varied features of topography which present themselves in many places.

Erosional Forms in Gently Inclined Strata. — Where disturbance of the sedimentary beds due to mountain-making dies away in the level plains country, the strata over wide areas may have a gentle angle of inclination. The same thing may occur also in the forming of a plateau, or in the faulting down of broad masses. In

such cases, since strata are almost invariably composed of hard, strong, and more resistant layers alternating with soft, weak, less resistant ones, there result from erosion topographic forms composed of a long gentle slope on one side, with an abrupt, or even precipitous, descent on the other. The long slope is maintained by the back, or upper face, of the resistant layer, while its thickness determines the height of the abrupt slope or cliff, as shown in Fig. 303. Such an arrangement with long out-slope is known as a *cuesta* from the Spanish name for them in the Southwest, and a cliff of this nature is often called an escarpment. Excellent examples of such cuestas are found in the region of the Rocky Mountains and, on a large scale, in the Colorado Plateau country. In some cases the hard stratum may be a sheet of lava. If the strata were horizontal the escarpment might through erosion extend entirely around it and we should then have a table-land, or mesa. See page 36.

CHAPTER XVI

ORE DEPOSITS

Definition of Ores. — The term *ore* is very widely used to designate anything that is mined from the earth for the uses of man. In a more strict and technical sense, however, it generally denotes those materials, parts of the earth's outer shell, from which *metals* may be profitably derived, and substances like coal, and salt, and stone or clay, which are used in their native condition, are excluded. Hence, in thinking of ores we usually connect them with metals, and it is in this narrower sense that the term is used in this chapter.

Ore Minerals. — Nearly all the different kinds of metals are made use of to-day, either as simple metals, or in some form of chemical compound. In addition, other substances, such as sulphur, phosphorus, etc., are mined and used. It is necessary, therefore, to enable us to study the occurrence and nature of ore deposits, to choose a few of the more important types as examples and concentrate attention upon them; for this purpose, we may select the ores of *gold, silver, copper, lead,* and *iron,* and they will be chiefly used as illustrations. Of these five metals gold mostly occurs as the native metal. Silver and copper also occur in places as native metals, and important mining districts yield them in this condition. The metals are found also in combination with other elements as minerals, and lead and iron, in ores, occur only in this way. Thus silver occurs combined with sulphur, often associated with arsenic; copper is found combined with oxygen, as an oxide; with sulphur, as a sulphide and sulphate, and also as a carbonate; lead occurs as a sulphide, as a carbonate, and as a sulphate; iron occurs as oxides, carbonate and sulphide, though this latter is not mined for iron, but sometimes for sulphur. There are, of course, other combinations of these metals in the form of minerals, but we are now concerned only with those which are important as ores. It should not be thought, however, that the metals and their ore minerals, only occur, and must be mined, separately; while this is true of iron ores, those of the other metals mentioned very commonly occur together, often in very intimate association, and such combined ore

minerals may be exploited for several metals. The facts mentioned above are shown in the little table below where they can be readily seen.

	Metal	Sulphide	Oxide	Carbonate	Sulphate
Gold	occurs	......	......	......	......
Silver	occurs	occurs	......	......	......
Copper	occurs	occurs	occurs	occurs	occurs
Lead	.....	occurs	......	occurs	occurs
Iron	.....	occurs	occurs	occurs	......

Gold occurs also in combination with tellurium, and both it and silver are found, often in very valuable quantities, in the ore minerals of other metals, such as those of copper and lead, in a state of such minute particles that their exact condition is not known. Thus a large part of the silver is obtained from galena, an ore mineral of lead, mentioned below. Silver also occurs combined with chlorine and with arsenic and antimony in combination with sulphur.

Important Ore Minerals. — The *properties* of the uncombined metals are so well known that they need no further mention. Reference to the table above shows that the chief forms of combination, in which the metals mentioned occur, are oxides, sulphides, carbonates and sulphate. Of these the sulphides, or sulphurets as they are sometimes called, are usually dark, heavy, opaque minerals with metallic looking appearance and luster. The oxides are in some cases metallic looking, but often less metallic appearing and even earthy. The carbonates and sulphates are not metallic in appearance but white or colored. Some of the chief minerals which yield ores are found in the list below and a brief description of them will be found in Appendix A.

List of Illustrative Ore Minerals

Silver.	Argentite,	Ag_2S
Copper	Chalcopyrite,	$CuFeS_2$
	Bornite,	Cu_5FeS_4
	Chalcocite,	Cu_2S
	Cuprite,	Cu_2O
	Malachite,	$CuCO_3Cu(OH)_2$
	Azurite,	$(CuCO_3)_2Cu(OH)_2$
Lead.	Galena,	PbS
	Cerussite,	$PbCO_3$
	Anglesite,	$PbSO_4$
Iron.	Magnetite,	Fe_3O_4
	Hematite,	Fe_2O_3
	Limonite,	$2\ Fe_2O_3 \cdot 3H_2O$
	Siderite,	$FeCO_3$.

This list is merely illustrative of the important ore-forming minerals; there are many others which at times and in places may also become valuable sources of these metals.

Oxide and Non-Oxide Minerals. — Inspection of the list above shows that the ore minerals may be divided into two classes, native metals and sulphides which contain no oxygen, and oxides (and hydrated oxides), carbonates and sulphates which do. These ore minerals may thus be separated into oxide and non-oxide groups. It has been previously shown, page 338, that there is a zone which reaches from the surface down to the level of ground water, in which the rocks and their contents may be acted upon by the agencies of weathering, and that this is usually a region of change and oxidation of the outer shell. Below this the presence of the ground water excludes in large part the air, and the changes which go on are those of a chemical nature produced by the water itself and by the substances which it may hold in solution and may deposit. Experience in mining teaches that in the upper zone the ore minerals are most likely to occur as carbonates, sulphates and hydrated oxides; below this, they occur chiefly as sulphides, and in the case of iron as non-hydrated oxides, while metallic silver and copper may be also produced by the oxidation and alteration. The natural conclusion is that the ore minerals were originally mostly sulphides and have been changed by atmospheric agencies into the oxidized minerals and metals we now find in the upper zone. The importance of this fact in understanding properly the nature of ore deposits will appear later.

Native metals are found both above and below the level of ground water. This seems to depend in the case of gold on its chemical capacity to withstand the action of the atmosphere in producing oxidation. Whether the copper and silver were originally deposited in the rocks as native metals is a point that will be considered later.

Mode of Occurrence of Ores. — The ore minerals may occur in a great variety of ways. In one, for example, like magnetite, the oxide of iron, they are sometimes thinly scattered through a mass of rock in small particles, and the occurrence may be valueless because so large an amount of material must be mined and treated to secure a relatively small amount of metal that its value would not pay for the operation. Where fine particles of gold, however, are disseminated through rock or gravel, the great value of the metal may render the working of such a deposit extremely profitable. In most deposits which have proved profitable, the ore minerals have been

segregated, or the containing rocks enriched with them, to form the ore bodies. The modes of occurrence of such ore deposits are of many different kinds depending on a great variety of causes and circumstances. Thus the ore may fill fissures or seams in the rock and form veins; it may be found filling cavities of various shapes and of differing origins; or it may be in the form of beds or lenses lying between sedimentary strata, as is so often the case with iron-ores.

Volume of Ore; Associated Minerals. — It must not be supposed that ore minerals are generally found in a solid mass filling a cavity in the rocks. It is true that such occurrences have been known in special cases or for limited distances, but they are rare, and in the great majority of deposits the metallic minerals form only a part, and often a very small part, of the material filling the cavity or making up the vein. With gold the actual volume of the metal is only a minute fraction of the material which composes the vein, and which forms "ore" and is mined for the great value of this relatively minute gold content.

On the other hand, the fact that iron is used in great quantities indicates that its value as a metal must be small compared with gold, and iron must, therefore, be relatively abundant and occur in large volumes.

It is evident, then, that ore deposits filling cavities, fissures, etc., consist of two things, ore-forming minerals, and associated substances which are known as "*gangue*," an old mining term; these, if the metallic content is of value sufficient to be profitably extracted, comprise the ore. Although gangue may be composed of many minerals, in most cases it is formed of very common substances, or a mixture of them, the chief ones being *quartz* (silica), and carbonates, such as *calcite* (carbonate of lime), *dolomite* (carbonate of lime and magnesia), *siderite* (carbonate of iron); less commonly, perhaps, *barite* (sulphate of barium) and *fluorite* (fluoride of lime), and sometimes rhodonite and rhodochrosite (silicate and carbonate of manganese). In certain cases it may also consist of valueless metallic minerals, or of altered country rock. Where oxidation of the ore deposits has not been complete there is also apt to be associated with the ore minerals sulphide of iron, *iron-pyrites* or *pyrite* (FeS_2). This may occur at times in large amounts and where abundant its presence in the rocks is usually indicative of mineralization. It is not used as a source of iron, but is mined in some places for the sulphur it contains, as previously stated.

Other gangue minerals might be mentioned, but the above will serve as examples, and descriptions of them will be found in Appendix A.

Classification of Ore Deposits

Introductory. — In the foregoing paragraphs some general introductory statements concerning ores and their occurrence have been given and it is now necessary to consider the classification of the deposits which contain them.

At the outset, we can divide them into two great classes, which we may call *primary* and *secondary,* in the sense that the primary ones are now found in the position in which they were originally formed in bed-rock, while the secondary ones have been clearly shifted from their previous to their present position by some agency, or set of agencies, and are thus products of disintegration. Thus, if we find particles of a metalliferous mineral as part of the structure of a fresh unchanged igneous rock, it is natural to suppose that the ore is in its original place of formation, and to call it primary, while on the other hand, when we see grains of gold mingled with the sand and gravel of a stream bed, it is equally natural to infer that it has been shifted from its original position and that, consequently, it is a secondary deposit. We shall consider first the primary ones.

Primary or Bed-rock Ore Deposits

Division into Families. — The primary class of ores, deposited in their present positions, may be subdivided into two families depending on their relation to the rocks which enclose them. In the first, the method of occurrence shows us that both the ores and the rocks have been formed at the same time, they are contemporaneous; in the second, it is evident from the structure that the rocks were formed first and that subsequently by some agency the ores gained entry in these rocks by filling cavities or by other means. The first we may then term *contemporaneous* ore deposits, the second *subsequent* ore deposits; they are also called respectively *syngenetic* and *epigenetic,* from the Greek, meaning in the one case "born with" and in the other "born upon."

Contemporaneous, or Syngenetic, Deposits. — Cases where the ores have been formed at the same time as the rocks which include

them fall into two groups, depending on whether these rocks are *igneous* or *sedimentary* in origin. In the first case, the masses of metalliferous substance, like the component mineral grains of the rocks, have been made by the cooling and crystallization of a molten igneous magma, as previously explained under the discussion on pages 324 and 325. They are, therefore, to be regarded as a *phase of igneous rocks* and we shall term them *type A* of ore deposits.

In the second case, the ores have been laid down from water as precipitates in the same way that the sedimentary beds have been formed, and just as the sediments are sometimes chemically (limestones), and sometimes mechanically (sandstones), deposited, so also are the ores. The contemporaneous ores made in this way we may call *sedimentary ore deposits,* and they form *type B.* The most important examples of these are to be found in certain iron-ore beds, whose mode of formation has been already discussed. See page 181.

Subsequent, or Epigenetic, Deposits. — In those cases where it is clear that the ore bodies are later than the rocks that enclose them we have learned from a great mass of evidence, part of it direct but most of it indirect, that the metalliferous substances have been deposited from solutions. We infer also that in the great majority of these cases the solutions were hot, often so hot that they were either actually or potentially in the gaseous condition. Either in the form of hot solutions or vapors the ores were brought and deposited; the probable origin of these solutions, or vapors, is discussed later in an appropriate place.

The solutions may deposit their metallic content, (*a*) by filling previously existing cavities of some size in the rocks, or (*b*) in cavities which they make themselves by dissolving rock particles and contemporaneously depositing their burden in the places thus formed, or, by a combination of both.

C_1. *Fissure Veins.* — In the former case, *a*, we know from what has been previously stated (see page 354) that the rocks forming the outer layer of the earth's shell are much shattered and filled with fissures; we have seen how the ground-water moves in these fissures, and in a similar way, the hot fluids carrying ore-forming minerals in solution may also circulate. But such solutions, standing or moving in the fissure cavities, are in contact with their walls, and it is easy to imagine that they may become cooled, and deposit more or less of their burden upon the walls, since cooling in general lessens the capacity of liquids to carry substances in solution. Or, they may react chemically with the rocks with which they come

in contact and thus have their chemical composition changed, and, simultaneously with this, their ability to hold the mineral substances in solution, the latter being, therefore, deposited. We can

Fig. 304. — Gold-quartz vein; the mining discloses the width of the vein and the wall-rock on either side. Cook Mine, Central City, Colo.

imagine, for instance, that a solution is acid, and coming in contact with limestone it would be neutralized, with the formation of lime salts and the deposit of the metalliferous substances. Or

again, it is quite possible to conceive that cooling and chemical reaction may be working together to cause the ore deposit, and that from the operation of both factors, it would form all the more rapidly.

Such deposits naturally take the form of films, sheets, or crusts deposited upon the walls of the fissure, which may be partially or wholly filled by the successive sheets of deposited substances. Usually it is not ore mineral alone that forms the filling, but a mixture of this with a greater or lesser quantity of other minerals, such as quartz, calcite, barite, and the other gangue minerals previously alluded to. It is, indeed, common to find quite pure quartz veins in the rocks without ore-making, or even other minerals in them.

Such ore deposits are known as *fissure veins* and they are of the greatest importance, being one of the chief sources of gold, silver, copper and other metals. We may designate them as *type* C_1. See Fig. 304.

C_2. *Other Cavity-filled Deposits.* — Although fissures are undoubtedly the most common form of opening in the rocks, and the ore deposits in them are of such importance that they may be considered as a group by themselves, they are not the only shape in which cavities exist. The rocks are penetrated by cracks, crevices and jointing planes, and on a more minute scale there are the pore spaces between rock grains and, though of lesser importance, there are openings and cavities in soluble rocks, especially limestones, which have been dissolved out by circulating fluids, chiefly water containing carbonic acid. Such cavities may become the channel-ways, or receptacles, of ore-bearing solutions and, as in the case of fissures, have ore bodies deposited in them by a similar set of processes. We may place them in one general group and term them *cavity-filled ore deposits, type* C_2.

D. Replacement Deposits. — In the cases just discussed, we have considered that the opening or cavity has been already produced by a previous process before it becomes the receptacle of the ore-bearing solution and its deposits. As previously suggested, however (page 414, *b*), it is quite possible that the production of the cavity or cavities, by the solvent action of an ore-bearing solution and the deposit of mineral substances, may be a simultaneous one. There may be rock-particles which are chemically affected by the solution, whose activity as a chemical reagent may be greatly enhanced by its heated condition. In measure as the mineral grains of the rock are dissolved, so, molecule by molecule, they may be replaced by a deposit of ore-mineral in the exchange of substance. Thus by a

chemical replacement of the whole, or a part of its contents, more or less of a rock mass may give place to a body of ore, or become so enriched in metalliferous grains through its substance, as to form a valuable ore deposit. In allusion to its mode of formation we may term this a *replacement ore deposit,* and call it *type D.*

It is evident that between cavity-filled and replacement ore deposits no sharp line can be drawn; all degrees of gradation between them must exist. Yet at either end of this line of gradation each type stands clearly forth, and definite examples of them can be readily recognized by the experienced observer. It is, therefore, not only a matter of convenience, but of scientific value that the types should be recognized, especially in classification. This gradation of the various kinds of ore deposits is not confined to these two, but is more or less true of all the various kinds, and this fact is discussed later.

E. Contact-metamorphic Deposits. — We have already learned in Chapter XII (and page 350) that when a mass of molten magma is injected into sedimentary rocks in the form of stocks, laccoliths, dikes, etc., and there cools and solidifies to igneous rock, a variety of effects is produced in the enclosing rocks in the region of the contact, which are comprised under the general term of contact (or local) metamorphism. The main effect is the hardening, baking, and recrystallization of the beds and the production of new minerals in them, and is caused by the heated gases and solutions forced into them from the body of cooling and crystallizing magma. The entry of the magma may have shattered the beds to some extent, while the recrystallization usually causes shrinkage in their mass, and this contraction may display itself partly in cracks and partly in many minute openings among the minerals. Such cavities might serve as channelways through which heated liquids or vapors coming from the magma, and bearing metalliferous substances in solution, might pass, and in which they might deposit them, producing, where sufficiently concentrated, profitable ore deposits. Although they may resemble the foregoing types (*C* and *D*) in that they have been formed in cavities or by replacement, they have such very distinct characters that they must be considered in a class by themselves and we shall therefore term them *contact-metamorphic deposits,* or *type E.* They are sometimes of great importance and we shall have occasion to refer to them again in a later place.

Summary of Primary Deposits. — The discussion which has been given in the preceding sections in which the different kinds of ore deposits of *primary origin* have been briefly set forth may now be summarized in tabular form as shown below, for the student's convenience:

TABLE OF PRIMARY ORE DEPOSITS

Primary Ores, those formed in the place where they now exist.	
Contemporaneous (Syngenetic). Made at same time as enclosing Rocks.	1. As a Phase of the Crystallization of *Igneous Rocks.* (*A*) 2. Deposited as Sediments with *Sedimentary* Rocks. (*B*)
Subsequent (Epigenetic). Later in Origin than the enclosing Rocks.	1. *Pre-existent* Cavities filled by Deposits from ore-bearing Solutions. *a*, Cavities have the Form of Fissures; producing *Fissure Veins.* (C_1) *b*, Cavities have some other Form; making *Cavity-filled Deposits.* (C_2) 2. Formation of Cavity and Deposit of Ore simultaneous by *Chemical Replacement* of Rock-mineral. (*D*) 3. *Contact-metamorphic* Deposits. (*E*)

Secondary Ore Deposits

Introduction: Definition. — It has previously been shown in this volume that the rocks of the outer layer of the earth's crust are subject to many agents which tend to change and even to destroy them. Partly these agents are mechanical in their nature and partly they are chemical in action. Under the weathering of rocks, the formation of soil, and erosion, their activities have been discussed, and the results have been pointed out in the descriptions of the chemical work of underground water and the formation of stratified rocks.

But, in the same way as the rocks are subject to these agencies, so also are the ore deposits contained in them. The primary ores, described in the preceding sections, are likewise subjected to the chemical activities of the air and its contained gases and to those of the circulating ground-waters, as well as to the mechanical effects of frosts and moving waters. They tend to change chemically, to be oxidized, to pass from sulphides, for example, into oxides, hydrated oxides, carbonates, sulphates, etc., as mentioned in a previous section, and, after such changes or during the process, either to go into solution and be carried away, or to be broken up and transported elsewhere. If taken in solution they may be carried into the ocean and added to that great ultimate reservoir of soluble materials and thus, in a sense, be lost; but on their way, under proper conditions, they may be again deposited in some place and thus give rise to renewed and even concentrated ore deposits. Or, if transported mechanically, they may through natural causes be concentrated in

some particular place and thus again form a valuable deposit of metals, or their ores.

All such deposits of which there is clear evidence that they have been *moved* from their original position to the ones which they now occupy, and of having thus been shifted by some set of processes, are termed *secondary ore deposits.*

Kinds of Secondary Deposits: Chemical, Mechanical. — In contrast with the primary ore deposits the secondary ones require only a very simple classification and may be divided into two groups, which, as foreshadowed in the previous paragraphs, depend upon whether they have been *chemically,* or *mechanically,* moved and concentrated.

In the *chemically concentrated ore deposits* the most important cases are those where the ores have not been moved any great distance, but chiefly from upper to lower levels of the deposits themselves. By this process of solution, transfer and redeposition, a concentration of ore minerals may occur which produces, in the midst of what would otherwise be a lean deposit of little worth, ores of great richness and value. Such places may be called *enrichment zones,* and as they are of great importance in mining operations, they are more fully treated in a following section.

The *mechanically concentrated ore deposits* represent those cases where the rocks or mineral substances surrounding the ore minerals or metallic particles have been acted upon by weathering and erosion and carried away, leaving them behind. This presupposes that the ore minerals or metals are not changed in such a way as to be taken into solution and removed; to be mechanically changed, they must remain in some insoluble form. They are also usually heavier than the soil particles, and their greater specific gravity causes them either to remain and gradually accumulate on the site of the deposit, or, if carried away by stream action, to accumulate in particular places and thus form workable deposits. The breaking down of quartz veins containing specks of metallic gold and the accumulation of the latter in the sands and gravels of stream-beds is an illustration of this.

General Classification

The brief descriptions of all the different kinds of ore deposits which have been given in the preceding pages may now be summarized in the form of a table which will serve to show their classification. It includes the preceding table of primary deposits a little differently expressed.

TABLE SHOWING CLASSIFICATION OF ORE DEPOSITS

Class	Period of Formation	Mode of Origin	Name
Primary: Deposited in their present position.	*Contemporaneous* (with enclosing rocks), Syngenetic.	Phase of *Igneous* Rocks.	*A. Igneous* Ore deposits.
		Deposited as *Sediments.*	*B. Sedimentary* Ore deposits.
	Subsequent (later in origin than enclosing rocks), Epigenetic.	Filling of *existent* cavities by ore-bearing solutions.	C_1. *Fissure Vein* Ore deposits. C_2. *Cavity-filled* Ore deposits.
		Chemical replacement of minerals in rocks by ores in solutions (or gases).	*D. Replacement* Ore deposits.
		Contact of igneous rock.	*E. Contact-metamorphic deposits.*
Secondary: Changed from their previous to their present position by some agency	*Moved.* Ore deposits, originally of foregoing kinds, acted upon by various processes and shifted in position, thus later.	*Chemical* solution, and concentration by redeposition.	*F. Chemically concentrated* Ore deposits (enrichment zones).
		Mechanical breaking down, transport and concentration of ores.	*G. Mechanically concentrated* Ore deposits (Placers).

The above classification is based upon clearly defined and definite types of ore deposits, and also upon theoretical considerations. But it must not be supposed by the student that all ore deposits belong very sharply or clearly in one or the other of the above divisions. It is true that a great number do, but many, perhaps the majority, exhibit a commingling of these types to a greater, or lesser, degree. Thus, in a fissure vein belonging to the primary class there may be an enrichment zone of the secondary class, and the deposit is thus partly primary and partly secondary. Or again, iron ores deposited as beds in the sedimentary strata are for the sake of convenience considered as primary, just as it is convenient to consider the stratified rocks as a primary division of all the rocks, although they have moved from their original place of formation.

By inspection of the last column in the table it will be seen that there are eight important types of ore deposits, and we may now state their more important features with illustrative examples.

Important Characters and Examples of Ore Deposits

A. **Igneous Ore Deposits.** — In the chapters devoted to volcanic action and igneous rocks it has been shown that when the magmas, the molten fluids of the earth, solidify into rocks they generally undergo a process of crystallization, so that the resultant mass consists of interlocked mineral grains. Mingled with the more important constituents are more or less intersprinkled grains of magnetite, or some other ore mineral of iron. It is conceivable that during the process of crystallization, through movements in the fluid mass, and owing to other causes not yet fully understood, the grains of iron ore mineral might be largely concentrated in certain places in a rock body and give rise to workable deposits.

It is held that this is the origin of some iron ores, as in Sweden, which have been worked. It is also thought by many that some copper deposits have been made in this way, the copper being associated with iron and sulphur in the mineral called chalcopyrite. But while these, and some other things of importance mentioned below, may occur in igneous rocks, the ore deposits of this kind, when considered in relation to the other ways in which ores are found, are really of minor importance.

In most cases where iron ore occurs concentrated in a rock mass, the iron and oxygen are apt to be associated with the semi-metal titanium in the mineral called *ilmenite* ($FeTiO_3$), mingled in grains with magnetite (Fe_3O_4). Until recently, owing to the infusibility of ilmenite and the presence of the titanium, no economical method for the smelting and extraction of the iron from such ores had been found; now electro-magnetic methods of separation of the pure iron ore from ilmenite are beginning to be used. Large bodies of such titanic iron ore, as it is often called, are known to exist in Norway, Canada, the Adirondacks and other places, and their utilization has now commenced.

Among the igneous ore deposits may be mentioned those of nickel and chromium, metals used for various purposes; these occur in segregated minerals in certain igneous rocks or in the products of their decay. Platinum and the diamond also originate in certain igneous rocks; the diamond mines of South Africa being in the decayed rock filling old volcanic necks. See remarks on peridotite, page 332.

B. **Sedimentary Ore Deposits.** — The most important examples of these are the iron ores which are found as layers or huge flattened lenses in the sedimentary strata, as previously mentioned. Their mode of formation has been rather fully discussed in Chapter VII, page 181, and from what is there stated it may be inferred that these ores are chemical precipitates, sediments made by the action of bacterial life. It is possible also to consider that in some cases they may have been precipitated by simple chemical reactions without the aid of life. Or again, it is conceivable that in the breaking up

and erosion of the original rocks the iron-ore particles were not removed by solution but carried away as mechanical sediments, like other soil particles, and by virtue of their higher specific gravity were concentrated in particular places, thus forming the deposit. In this case they are mechanical in origin. Iron-ore deposits are often of vast size, covering hundreds of square miles, or more. A good example of them is seen in the great beds of "Clinton" ore which stretch from New York State to Alabama, and which are further considered in an appropriate place in the second part of this volume.

The position of such beds depends on that of the associated strata; if flat or inclined or folded, so are the included ore-beds. Originally the ores were probably hydroxides (limonite) or carbonate (siderite). But it may have happened that the region has been subjected to orogenic forces, to folding and to metamorphism. Then, not only the stratified rocks, but also the contained ore-beds will be metamorphosed and changed; like the rocks they may become hard and crystalline, lose water or carbonic acid, and become anhydrous oxides (hematite and magnetite). Also intrusions of igneous rock in the vicinity of the ore-beds may produce local metamorphic effects, and act in other ways as well. Thus, the character of an originally simple deposit may become much complicated and its origin obscured. The great iron-ore deposits of the Lake Superior region afford a striking example of this. They appear to have been laid down as chemical sediments, but have since suffered from regional and contact metamorphism, and from chemical solutions which have more or less moved and concentrated them. They are thus of complex origin and afford a good example of the commingling of types previously mentioned.

C_1. **Fissure Veins.** — In a previous section it has been shown that solutions carrying ores may deposit them in fissures and cracks in the rocks, and that these form one of the most important kinds of ore deposits. The reason for this is easily seen when we reflect that cracks and fissures are the most abundant and natural form of openings or cavities in the outer rocky layer in which the fluids can circulate. The thickness, depth, and extension of such veins, like the fissures which they fill, are very variable features; they may be only a few inches (Fig. 305), or many feet and even yards in thickness; veins have been followed downward several thousand feet before increasing difficulties caused an abandonment of the working; they may extend only a few hundreds of feet laterally, or many miles. As with dikes, it is natural to think of a vein as a vertical sheet or wall traversing the rocks, so the same terms are used to define its position and departure from the vertical, see page 314; we speak, therefore, of its *trend* and *hade*. The same terms

are also used, it will be recalled, page 359, with respect to fissures and especially fault fissures, which naturally have a close connection with veins. Very often, bearing in mind the resemblance to inclined strata, which are referred to the horizontal instead of the vertical, the terms *dip* and *strike* are used instead of hade and trend;

Fig. 305. — View of a small fissure vein, two inches wide. The containing wall-rock is seen on either side, beyond the narrow dark line. One-half natural size.

this is the more common usage in America. And again, recalling what was said with respect to fault fissures, page 360, we speak of the upper contact of a vein with the enclosing rocks as the *hanging-wall,* the lower one as the *foot-wall.*

As previously mentioned, the ore mineral is usually only a portion of the materials composing the vein; the proportion between ore minerals and gangue minerals is a very variable one, not only between different veins, but in different parts of the same vein, and this forms one of the uncertainties of mining operations. The varia-

tion in a vertical direction may be original, or it may be a secondary effect, as explained later under alteration and enrichment zones. There may also be great variations in the horizontal direction or extension of the vein, dependent upon several factors; such as a change in the nature of the country rock, which would affect the chemical reactions that caused the solution to deposit the ore; or by the contact with a cross-cutting body of igneous rock, whose advent stimulated the activity of the ore-bearing fluids; or by the crossing of another vein.

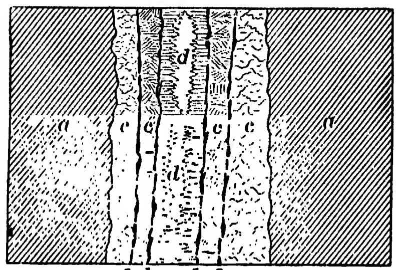


Fig. 306. — Section of a fissure vein: *aa*, wall-rock; *bb*, layers of ore; *cc*, gangue; *d*, open cavity or vug, lined with crystals.

It has been pointed out that a fluid-depositing material in a fissure would naturally do so by forming coatings, crusts, or films upon the walls. Each wall would receive a layer, and as the composition of the moving liquids changes from time to time, so the nature of the layers would change, one of gangue mineral being succeeded by one of ore, and this perhaps repeated several times, as illustrated in Fig. 305. The section of such a vein may thus exhibit a banded appearance which is known as the *ribbon-structure*. The fissure may be tightly and compactly filled with the ore, or it may happen that the last coatings do not completely fill it; in this case there are usually flattened lenticular cavities lined with crystals from the last deposition separating the latest deposited crusts; these are termed *vugs*. See Fig. 306. Often the actual vein is separated from the country-rock by a thin layer of decomposed rock or clay, or other minerals, known as the *selvage* or, more commonly, *gouge*, which coats the contact.

The irregularities of veins are very great. They may widen, giving rise to chambers of ore, which when large and rich have been called *bonanzas*, or they may *pinch* until only thin films or stringers are left to show their continuation, to again widen beyond. or finally end. They may twist or turn in their course, branch, and perhaps re-unite, send out stringers into the

surrounding rocks, be cut by other veins or by dikes. Or again, masses of country-rock, known as *horses,* may be encountered in the vein, or a major vein may be composed of a number of closely parallel minor ones, or finally, the vein may represent merely a shattered zone of rock whose interstices are filled by interlacing films of ore mineral and gangue. Thus countless variations from the simple type occur, depending on the nature of the water ways through which the solutions passed. Veins are frequently cut by faults with greater or lesser amounts of displacement, a fact which forms one of the most serious problems of mining operations. All that was said about faults in the discussion of them in Chapter XIV may be here considered with profit.

One of the most interesting and important examples of fissure veins is found in those which have furnished so large a proportion of the world's supply of gold. The vein typically consists of massive white quartz through

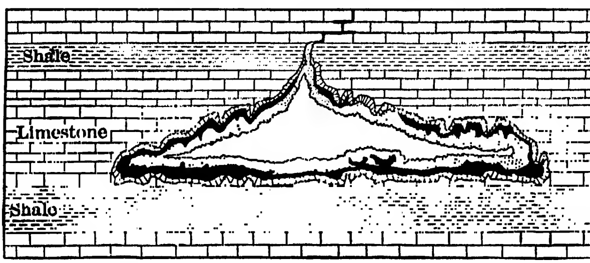


Fig. 307. — Cavity-filled deposit. Shows an open cavity coated by deposited layers of gangue and ore mineral, the latter black. The stalactites and stalagmites of the original opening show the cavity existed before the deposition. Masses of ore mineral fell from the roof before the last deposit was made.

which is scattered more or less yellowish masses of iron-pyrites. The gold forms only a minute part of the whole and is seen, as a rule, only in occasional tiny specks of the native metal; it may be mostly concealed in the pyrites. Veins of this nature are found in many parts of the world, some of the most noted being in California and other parts of the North American Cordillera. Not only gold, but silver, copper, and many other metals are found in veins, usually with certain associations of minerals that accompany them;* as copper and silver ores in the Butte district of Montana, and ores of silver, cobalt, etc., in the veins at Cobalt, Ontario.

The probable origin of fissure-vein ore deposits will be considered later, after the next and closely related kinds have been described.

C_2, *D*. **Cavity Fillings and Replacement Deposits.** — It has been previously pointed out that no sharp line can be drawn between these two classes of deposits, for it is obvious that in some cases it must be very difficult, if not impossible, to determine whether a cavity previously existed, or was made by the ore-bearing solution eating away the rock and leaving the ore in its place. In a typical cavity filling we conceive the ore deposited in some existent channel way or opening made in the rock, see Fig. 307; in a typical re-

placement deposit, we conceive a porous rock penetrated by the ore-bearing solution and an exchange, volume for volume, of rock substance and ore. See Fig. 308. An example of the latter would be the effect of an acid solution of copper sulphate upon limestone, by which copper carbonate is deposited and sulphate of lime (gypsum) is carried off, thus $CuSO_4 + CaCO_3 = CuCO_3 + CaSO_4$.

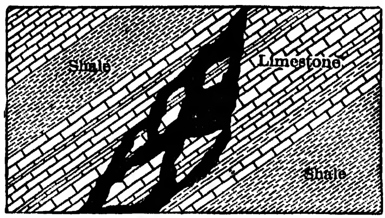


Fig. 308. — Replacement ore deposit. The dark area, ore. The suspended blocks of still unaltered limestone in the ore body show the cavity could not have been an open one when the ore was deposited.

The equation given above represents the chemical exchange in simple terms; in reality it would be much more complicated in the supposed case.

One of the most important examples of ore deposits of this nature is found in the silver-lead ores which in Colorado, Montana, Idaho and other parts of the Rocky Mountains' region have furnished such great quantities of metals and whose exploitation has done so much toward the development of the western states. In these cavity fillings, the ore bodies may be of extremely irregular shapes and sizes. Often they are long and rudely cylindrical in form and are termed chimneys of ore. At other times they may take the character of flattened lenses lying between strata; as in the lead and zinc ores of the Mississippi valley. They are sometimes of great size.

Origin of Epigenetic Ore Deposits. — In fissure veins, cavity fillings and replacements it is quite clear, and generally agreed to, that the ores have been deposited by solutions, but in regard to the origin of these solutions, and to the circumstances under which the ores were formed, widely different views have been held, some of which are now obsolete. To state them and discuss their merits would take entirely too much space, and we shall therefore content ourselves with giving that one which now receives general acceptance, and which is supported by the greatest body of evidence.

This view regards the solutions as either (1) *ascending* ones having a magmatic origin, or (2) those formed by the ordinary circulation of ground water (meteoric water). With respect to the first (1) it will be recalled that under volcanic action, under hot-springs, and under the discussion of igneous rocks, the existence of volatile constituents in the earth's magmas has been repeatedly pointed out, and that, as the magmas rise into the outermost shell of the

crust through changes of stress and other causes, these volatile components escape through loss of pressure, or are excluded in the process of crystallization and solidification. We must imagine that originally they are in the gaseous condition as they leave the magmas, but through cooling and accumulated pressure they may pass into the liquid state, or meeting descending waters, they may heat and charge these with the substances of which they are composed. Among these latter are the various acid gases, which have been mentioned under volcanoes, water vapor, silica, alkalies, and other compounds, and especially the metallic elements which give rise to the ores. It should be conceived that after the intrusion of a body of igneous rock there comes a period, attending and following its solidification, when these volatile compounds are passing off through fissures and openings in the rock body itself and in the surrounding and covering masses of rock, and are producing an active circulation in them of heated solutions; it is at this period, the early part of which is known as the "pneumatolytic" or gas-forming stage, and from these solutions, that the ores are deposited. Obviously the truth of this view will depend very largely on the relation which can be traced between the occurrence of igneous rocks and that of the ore deposits, and this has been found to be, in a very great number of cases, a very close one indeed, the ores being closely adjacent to the igneous masses, or in their vicinity. In regard to the other case (2) it is thought that the ground waters circulating in the rocks have taken mineral substances, generally sparsely distributed through large rock masses, into solution, and moving into places where, probably through a change in the composition of the rocks, chemical reactions have occurred, they have deposited these mineral substances in concentrated bodies, giving rise to the ore deposits.

According to their original position and the conditions under which they were formed these epigenetic deposits have been divided into the following groups.

1. In connection with Igneous Rocks.

W. Deposits formed at great depths under high temperature and pressure.

- *a. Contact-metamorphic Deposits.*
- *b. Deep Vein Zone Deposits.*

X. Deposits formed at Moderate Depths by Hot Solutions.

Y. Deposits formed at Shallow Depths by Warm Solutions.

2. Not connected with Igneous Rocks.

Z. Deposits formed near the surface by Cool Meteoric Waters.

W, a. Contact-metamorphic Deposits.—These have been already mentioned as forming type *E* of our table of classification, and we go on to give further details regarding them. They are found immediately adjacent to bodies of intruded igneous rock, usually of feldspathic nature, such as granite, syenite, granite porphyry, etc., which have been exposed by erosion. In the contact zone (pages 350-351) they are especially apt to occur in limestones or calcareous shales and are irregularly distributed in generally formless masses which vary greatly in size. A common feature of the ore is that it is a mixture of silicate minerals, of which garnet may be mentioned as representative, with the oxides and sulphides of the metals. They do not appear usually to have been deposited in fissures and open cavities so much as to have been forced under the conditions of high temperature and pressure into the pores and minute openings in the rocks; in part they may be replacements of the country rock. The metals which occur in them are iron, copper and zinc, less commonly gold, silver and lead. See Fig. 309.

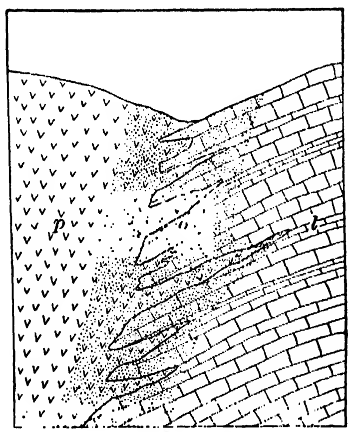


Fig. 309.—Diagram of a contact ore deposit: *p*, porphyry in contact with *l*, limestone. The zone of contact, *o*, has been affected by ascending solutions which have altered the rocks and deposited telluride of gold in them. Judith Mts., Mont.

There may be mentioned here a small group of ore deposits which are closely related to the contact-metamorphic ores (and those of the deep vein zone) on the one hand, and to deposits of pure magmatic origin of type *A* (page 421) on the other, and thus stand between them. They may be termed the "pneumatolytic" group. They may occur, partly in the igneous rock body, or partly in the contact zone immediately adjacent, and are usually found associated with granite or granite-porphyry. They are characterized by the presence, along with the metalliferous minerals, of others containing volatile substances from the magma, such as topaz and fluorite which contain fluorine, and tourmaline which contains boron. Some of the ores of tin offer good examples of this group.

W, b. Deep Vein Zone Deposits.—Like the contact-metamorphic group these ore deposits have been formed under high temperature and pressure in great depth near bodies of igneous rock. Unlike them they have been

deposited in definite openings, usually distinct fissures, made by previous fracturing of the rocks. They may replace to a large extent the original wall rocks of the openings. Often the veins may be in the igneous rock itself. They only become exposed after deep erosion has occurred. The minerals composing them are similar to those of the contact-metamorphic deposits, but quartz as a gangue is more common. Gold, tin, iron, copper, and other metals are found in these deposits. The gold-bearing quartz veins of the southern Appalachians are a good example of them; the tin and copper veins of Cornwall in England are, perhaps, those best known.

X. Deposits formed at Moderate Depths.—These include many extremely valuable ore bodies which furnish gold, silver, copper, lead and zinc. The great copper deposits of Montana, Utah, Nevada, Arizona and others of our western states, and in Mexico and other places, belong mostly in this class, as well as the gold-quartz veins of California. In fact most of the ore deposits of the Cordillera are of this nature. They are found in or near masses of igneous rocks, generally those of intruded occurrence, and have been exposed by erosion. They have been formed by hot ascending solutions which have deposited the ores, usually in fissures, forming veins, and these may extend farther out from the igneous bodies than the groups previously described. From the geological evidence, and the nature of the minerals they contain, they are inferred to have been formed for the most part at depths between 5,000 and 10,000 feet, at temperatures from 175° to 300°, and pressures from 150 to 400 atmospheres. The veins are apt to show the ribbon structure, page 424. Sometimes the deposits are of the replacement type. Quartz is very common as a gangue mineral, whereas the high temperature minerals, such as garnet, pyroxene, topaz, tourmaline and biotite, found in the preceding groups, appear to be absent.

Y. Deposits formed at Shallow Depths by Warm Solutions.—Like the foregoing groups these deposits are apt to be situated in igneous rocks or in stratified beds near them. The igneous bodies are generally intrusive masses of the smaller kinds injected not far below the surface, such as sheets, laccoliths, and dikes, or the metals may occur in surface flows. The deposits have been made, it is inferred, generally speaking, at depths not greater than 5,000 feet and in temperatures not often exceeding 150°, and have been exposed by moderate erosion. Quartz, calcite, dolomite, barite, and fluorite are common gangue minerals; in certain copper ores zeolites (hydrated crystalline silicates) occur also. High temperature minerals are wanting. The solutions were ascending from the heated masses below and deposited the ores in fissures, making veins, or irregular bodies in shattered rocks, or by replacement along the walls. The chief metals found in these ores are gold, silver, copper, lead, zinc and mercury. They have furnished much gold, and a good part of the world's silver. The famous Comstock lode in Nevada is an example, as are the gold deposits at Tonopah and Goldfield and at Cripple Creek, Colorado. The deposits of native copper in northern Michigan near Lake Superior furnish another example and have long been famous for the enormous quantity of the metal which they have yielded. The copper occurs in strings, plates, and irregular masses in cracks and vesicular cavities of sheets of trap rock (page 332), and in hollow spaces adjoining conglomerates. The metal is accompanied by deposits of zeolites and calcite

in the vesicular trap, which have been deposited by the warm solutions. Basaltic rocks whose pores have been filled by calcite, zeolites, etc., are called *amygdaloids,* and copper, usually in small quantity, has been found frequently in them; the chemical processes which concentrated the metal and deposited it are not yet well understood.

Z. Deposits near the Surface from Meteoric Waters.—These are found mainly in normal sedimentary rocks, sandstones, shales, and especially limestones, and have no visible connection in many cases with igneous masses. The ores occur in irregular bodies, filling cavities, in areas of shattered rock, less prominently as veins filling fissures; in some cases they form flattened lenses lying along the bedding planes of the strata. They are in part replacement products. The chief metals furnished by them are lead, zinc and some copper. The ore minerals are not only sulphides but also carbonates, silicates and sulphates. Common gangue minerals are calcite, dolomite, and barite, with chert and jasper (siliceous substances).

The best example of these ores is found in the lead and zinc deposits of the Mississippi valley, especially in Missouri. They occur mostly along the bedding planes in limestones having a low angle of dip. It is thought that the descending surface waters take into solution the ore minerals, which are disseminated widely in minute quantities through great areas of rocks, and carry them laterally along the beds until, under favorable conditions, they deposit them in concentrated masses in particular places.

Though this may explain the concentration of the ore minerals it does not tell us how the metalliferous substances become disseminated through the strata, and on this point there is diversity of opinion, some holding they were deposited from sea-water along with the sediments; others by ascending thermal waters and some by referring them to supposed igneous masses in the depths, not yet exposed by erosion. No explanation has been as yet generally agreed upon.

Mingling of Types.—It is clear that between the different types of ore deposits *W* to *Z* described in this section, no sharp boundaries can be drawn; they may pass imperceptibly from one to the other or a given ore body may lie on the line between them. Thus in a region of igneous intrusion warm waters carrying metallic substances may rise to the surface and meeting descending surface waters may mingle with them and cause ore deposits of a mixture of types *Y* and *Z* described above. Also, for example, between deposits of type Z and the ores of chemically enriched zones described beyond, there may be gradations. Such transitions have been mentioned before and the student must always bear them in mind.

F. **Chemically Concentrated Ore Deposits.**—As has been previously mentioned, the most important of the cases where ores occur in profitable deposits through chemical concentration are in the so-called enrichment zones, found in connection with fissure veins, cavity fillings and the replacement bodies previously described, which are all epigenetic. Since, however, the subject is also involved with the important one of the alteration of primary ore deposits by meteoric agencies, and such processes of alteration are not

necessarily in all cases attended by movement and redeposition of the ore, it seems better to consider these processes and their results under the general heading of the alteration of ore deposits, which is done in a succeeding section.

G. **Mechanically Concentrated Ores: Placers.** — The method by which ores may be mechanically concentrated has been already explained, page 419, but a few words may be added to what has been given and some examples presented. Such a concentration could take place in one of two ways; either the surrounding rock could be chemically dissolved and its substance carried off, leaving the ore to accumulate, or both the rock and ore could be mechanically broken up by erosion and the ore concentrated by virtue of its higher specific

Fig. 310. — View of a gold placer mine in operation. Banks of sand and gravel containing the fine gold particles are being washed down by powerful jets of water into sluices where the gold is caught in pockets of mercury. La Grange Mine, northern California.

gravity. The first case occurs essentially with limestones, which as we have seen are soluble rocks, and in this way is explained the origin of certain deposits of iron and manganese oxides which furnish useful ores. The most striking examples of the latter are seen in the gold placers, or washings, where the gold, set free by the erosion agencies from the original veins in higher regions, is now in the sands and gravels of stream beds, as in California, Alaska and other places, from which it is obtained by hydraulic, dredging, and other processes. See Fig. 310. The essence of such processes consists in passing the auriferous material through some contrivance such as long narrow boxes or troughs, called sluices, which have cross bars, or riffles, at the bottom. The sand and gravel are washed along by a current of water, while the gold particles, on account of

their high specific gravity, sink, and are caught against the riffles. Sometimes in these pockets at the bottom of the sluice, the gold is made to come in contact with mercury, which absorbs it, and from which it may afterwards be recovered.

Mechanically concentrated ores of this nature, among which may be mentioned gold, platinum, tin, mercury, and gems, such as the diamond, sapphire, etc., as well, constitute undoubtedly the most primitive kinds of ore deposits which were worked by man.

Alteration of Ore Deposits: Enrichment Zones. — Like the rocks which enclose it, an ore deposit once formed is subject to

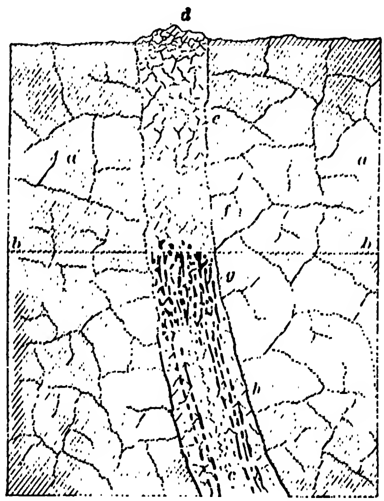


Fig. 311. — Diagram illustrating alteration of an ore-vein and a secondary enrichment zone: *aa*, country-rock; *bb*, level of ground water; *cd*, ore-vein; *d*, capping of gossan; *e*, leached and barren part of vein; *f*, concentrated oxidized ore with carbonates; *g*, secondary enrichment zone of highly metalled sulphides and metals; *h*, normal part of vein with unchanged, lower-metalled sulphides.

alteration and by the same agencies of weathering and surface waters with their contained gases. Under normal conditions, in unglaciated countries, we do not find, therefore, the upper portions of a metalliferous vein, down to the level of ground water, in the same state as that in which it was originally formed, but, on the contrary, with the metallic contents in a different set of mineral combinations and with a different arrangement. Whereas in the normal vein the metals may have been in combination with sulphur, as sulphides, and without oxygen, they are now carbonates, sulphates, or oxides, all oxidized forms, or possibly as simple native metals. We can, perhaps, understand this change best by the de-

scription and discussion of a particular case, selecting a rather simple one.

Let us imagine a copper vein, Fig. 311, consisting chiefly of quartz with intermixed masses of copper-iron-pyrites (chalcopyrite, $CuFeS_2$) as the ore, in its original, normal condition. The outcrop of such a vein on the surface shows merely as masses of cavernous rusty quartz, stained red to brown by oxide of iron. It may exhibit no trace of copper, the original ore having been completely destroyed by the action of the atmosphere and surface waters, the copper taken into solution and leached downward, while the iron is left as an insoluble colored oxide with the quartz. Such a rusty covering, or capping of an ore deposit, is very common and is known to miners as *gossan*, or "iron hat." On following the vein downward, at a variable distance, copper mineral is found, not the original unoxidized sulphide, but blue and green carbonates of copper; azurite ($2\ CuCo_3Cu(OH)_2$) and malachite ($CuCO_3Cu(OH)_2$), and, usually, more or less increasing downward in amount. These carbonates are due to the destruction of the original ore mineral by the oxygen and carbonic acid of the atmosphere and surface water, to the copper having been taken into solution, leached downward, and deposited. This continues down till the level of ground water is reached, which may in some cases be a distance of several hundred feet, whereupon a different condition of things will be found. Below this level, the ore is protected by the water from the oxidizing action of the atmosphere and the carbonates give place to sulphides. These sulphides are not, however, those of the original deposit, but others in which there is a much larger proportion of copper to sulphur. Thus the chalcopyrite, $CuFeS_2$, of the original deposit is replaced, for example, by *chalcocite,* Cu_2S, or rarely by metallic copper, Cu, thus showing the increase in the amount of the metal. This appears to be due to the leaching solutions, which carry the copper downward from the upper part of the vein, as mentioned above, and bring it below the level of ground water and in contact with the original sulphide ore minerals. Then, by chemical reactions the latter are changed into lower sulphides, containing a larger proportion of copper. Thus the portion of the vein at the level of ground water, and for a variable distance beneath it, is much richer in the metal than the general average of the normal vein below. This is known as the *zone of secondary enrichment,* and below it the vein eventually assumes its normal unchanged character. See Fig. 311. This illustration will serve to explain the origin of division *F* of our table of classification, *secondary ore*

deposits, in which the ores have been moved from their original position and *concentrated by redeposition by chemical processes.* The example has been selected for copper, but the process applies also to silver, and some other metals, and to other forms of deposit as well as to veins. Lead, however, though it forms an enriched zone of carbonate and sulphate above the ground water, has not been found secondarily concentrated in the sulphide zone below that level.

Numberless variations of what has been described above are met in different places according to varying circumstances, such as the different forms of veins and deposits, the different kinds of metalliferous and other minerals they contain, and the varied conditions to which they have been subjected, but it should be conceived as the normal process moving downward along the vein in proportion as the country is lowered by erosion. Not all of the metal leached down is necessarily redeposited, it may be largely, or even wholly, carried away in solution and lost. The leaching solutions coming from the surface may be, as explained under the formation of iron-ore, page 172, reducing ones which may convert the metals into the metallic state. Gold, which is not usually acted upon chemically by these solutions, is left in the rusty quartz of the oxidized part of the vein in the metallic condition, forming what is known as "free-milling" ore from the ease with which it can be directly extracted by mercury, and in contrast to that in the unoxidized part where it is mostly enclosed in unaltered iron-sulphide (pyrites), which has to be concentrated and treated by special processes to obtain its content of gold.

In mountainous and northern regions, like parts of the Rocky Mountains, Canada, and Alaska, which have recently experienced severe glaciation, it may be found that along with the general erosion of the country the former oxidized portions of veins and other ore deposits have been ground off and carried away, bringing the unoxidized sulphides to the surface. The retreat of the ice may have been too recent to permit of the formation of a new zone of oxidation, and the present surface line might pass through the former zone of secondary enrichment, or the surface line may be below it, in which case no enrichment zone will be found as the vein is penetrated. This latter case is by far the most common.

The facts which have been exposed above afford an explanation of the common view held by miners and prospectors that an ore-vein must grow richer in depth. Under usual circumstances with an oxidized vein this would be the case, until the zone of secondary enrichment is passed, when it will grow leaner in assuming its normal character, whereas, with unoxidized sulphides at the surface, as explained above, it will probably grow poorer in ore. This may be readily understood by conceiving different surface lines passing through the vein shown in Fig. 311.

Metamorphism of Ore Deposits. — It has been previously stated that no hard and fast lines can be drawn between the different kinds of ore deposits, that the types established in our classification merge into one another, and that, therefore, while these types serve as useful center-points around which the different kinds may be

grouped, intermediate varieties will be found between them. We have also seen that the deposits are subject to alteration and change of position by chemical agencies, which tend to alter them from primary to secondary ores, and it is easy to conceive that such changes may be slight, very great, or even entire. But there is also another factor which may affect ore deposits and may add to the difficulties which arise in correctly interpreting their origin and in classifying them, and that is the agency of *metamorphism.* The subject of the metamorphism of *rocks* has been previously discussed, page 339, and it has been shown that both stratified and igneous ones may be converted into gneisses and schists, marble, quartzite, etc., and that such changes may be *general,* produced by compressional processes of folding, etc., over wide tracts of country, or *local,* as in the zones about intrusions of igneous rocks, or a combination of both. Thus, just as *rocks* may be metamorphosed, so also may be the *ore deposits* which they may contain. In consequence of this, their original nature may be much changed and their origin obscured. Perhaps some of the most striking examples of this fact are to be found in beds of iron ore, laid down concordantly with the strata as deposits of non-crystalline, more or less earthy limonite ($2Fe_2O_3 . 3\,H_2O$), or siderite (carbonate of iron, $FeCO_3$), which by the agents of metamorphism attendant upon folding have lost their volatile constituents and become converted into hard, compact, more or less crystalline masses of hematite (Fe_2O_3), or magnetite (Fe_3O_4), often found in regions of metamorphic rocks. And other ores besides those of iron may be affected in a similar way.

Here, in part at least, may be placed the great iron ore deposits of the Lake Superior region. Originally sediments, perhaps chemical precipitates from bodies of water, they have since been changed by chemical agencies and in places concentrated in the hollows of synclines by downward leaching and chemical replacements, and have been affected by the action of regional and local, or contact, metamorphism. Later erosion, especially that of the Glacial period, has brought them to, or near, the surface and rendered them accessible to exploitation. The changes they have suffered render their interpretation one of the most difficult problems of economic geology.

APPENDIX A

MINERALS IMPORTANT GEOLOGICALLY IN ROCKS AND ORES

Introductory. — For the benefit of those who have had little or no previous training in mineralogy, the following brief description of the chief kinds of minerals, which have been mentioned in this book and are important geologically in rocks and ores, is appended. As has been shown in the foregoing pages they are the ones which mainly compose the rocks and soils and take part in important geological processes. If time permits, and the student is unfamiliar with them, it would be well for him to begin his course with some study of the descriptions here given, and he should have the opportunity of seeing and comparing representative specimens of them.

The most important rock minerals may be listed as follows:

Calcite, $CaCO_3$
Chlorite, $H_8(MgFe)_5\,Al_2Si_3O_{18}$
Clay (Kaolin), $H_4Al_2Si_2O_9$
Dolomite, $(CaMg)CO_3$
Feldspars, $KAlSi_3O_8$, etc.
Gypsum, $CaSO_4 \cdot 2\,H_2O$
Hematite, Fe_2O_3
Hornblende, $CaMg_3(SiO_3)_4$, etc.
Limonite, $2\,Fe_2O_3 \cdot 3\,H_2O$
Magnetite, Fe_3O_4
Micas, $H_2KAl_3(SiO_4)_3$, etc.
Pyroxene, $CaMg(SiO_3)_2$, etc.
Quartz, SiO_2
Rock-salt, NaCl
Serpentine, $H_4Mg_3Si_2O_9$
Siderite, $FeCO_3$
Talc, $H_2Mg_3(SiO_3)_4$

By observing the chemical formulas of the above minerals, some of which represent only one variety of what is really a group, it will be seen that they comprise silicates, oxides, and carbonates of the metals, with one sulphate and one chloride, which are of lesser importance. The silicates, which are compounds of metals with silicic acid (oxide of silica, SiO_2) form the bulk of the minerals which make up the massive rocks constituting the outer shell of the earth, and upon which the sedimentary formations rest, and also of the erupted volcanic rocks. Mingled with the silicates are smaller amounts of oxides, chiefly those of iron and silica. These minerals are for the most part anhydrous, that is, devoid of combined water. The carbonates and hydrated oxides and the sulphate are chiefly in the relatively thin films which the sedimentary rocks form on the surface of the globe. The salt is mostly in the sea. Hydrated oxides,

and silicates, and also carbonates, are the result of the action of weathering and the circulation of water and other chemical agents upon rocks composed of anhydrous minerals, and are therefore found in the outermost zone of the crust where these agencies are at work; they occur in metamorphic and sedimentary formations.

Physical Properties of Minerals. — There are certain important physical properties of minerals which serve to characterize them and to distinguish them one from another. These are, *crystal-form, cleavage, color, hardness,* and *streak.*

With regard to *crystal-form,* the molecules of minerals in most cases have the property of so arranging themselves during growth as to produce structures having not only definite physical properties but also characterized by geometric shapes; and such structures are known as crystals. Each mineral has its particular crystal form which it endeavors to assume if not interfered with during its growth. Figures of some of these forms are shown in the description of the minerals which follows. They are not commonly well developed in the crystal grains which make the rock particles on account of mutual interference during their growth.

Cleavage is the property possessed by many minerals of splitting or breaking more or less perfectly in certain directions through the crystal, and yielding smooth flat surfaces. A familiar example is mica, whose usefulness depends on its perfect cleavage. It varies greatly in different minerals, some, like quartz, being destitute of it.

The *color* of minerals is an almost obvious property; the color in powdered form may be quite different from the mineral in mass and is most easily seen in the *streak,* which is produced when a bit of the substance is drawn across an unglazed porcelain plate.

Minerals vary much in their *hardness;* thus gypsum may be scratched by the finger nail, while the diamond is not scratched by any other substance. Simple means of testing hardness may be found in the knife-point, a bit of feldspar, or one of quartz, each being successively harder than the former.

List and Description of Rock-minerals

Albite, see under Feldspar.

Amphibole, see under Hornblende.

Anorthite, see under Feldspar.

Apatite. — Occurs in hexagonal prisms, with ends rounded or capped by six-sided pyramids, greenish or brownish in color; is easily scratched by a knife; has no good cleavage. It is a phosphate of lime, with fluorine $(CaF)Ca_4(PO_4)_3$, and although sometimes found in large crystals it occurs chiefly in excessively

minute microscopic ones distributed through many kinds of rocks. While of no great geological importance it fulfills an important function in furnishing to the soil, when the latter is made by rock decay, the phosphorus so necessary to plant-life and (through the plants) to animals for their bony structures, etc.

Aragonite. — Calcium carbonate, $CaCO_3$, like calcite, but differs from the latter in its crystallization, which is orthorhombic. Lacks the cleavage of calcite, which readily distinguishes it. Colorless, white, or tinted. While it sometimes occurs as a vein mineral its chief geological interest is in the fact that it is the form of calcium carbonate which is chiefly deposited by organic life; thus it is a common component of many shells, especially in the pearly layers.

Augite, see under Pyroxene.

Biotite, see under Mica.

Calcite, carbonate of lime, $CaCO_3$. One of the most important of geological minerals. Often occurs in crystals, either pointed pyramidal, or prismatic, or flattened rhombohedral in shape; generally whitish in color, or clear transparent; sometimes tinted. Is often massive, filling fissures, or in grains, as in marble. Three directions of excellent cleavage not at right angles, forming rhombs. Easily scratched with a knife; effervesces readily in cold acid. Besides occurring with the properties mentioned, as filling veins and cavities and forming marble, calcite in the form of minute, not distinctly crystallized granules constitutes the cementing substance of the grains of various rocks, such as many sandstones; and in the limestones, chalks, etc., makes up the entire mass of the rock, or nearly so.

Chert, see under flint.

Chlorite. — This is used as a general name for a group of minerals whose exact chemical nature is not yet well known. They are hydrous silicates of aluminum, containing ferrous iron and magnesium. In outward properties chlorite is green to dark green in color, and like mica it has one very perfect cleavage, but unlike it the cleavage leaves although tough are not elastic. Although sometimes occurring in crystals which are flat six-sided tablets it is usually seen in scaly aggregates, which, although sometimes coarse, are more apt to be fine, producing massive forms. Chlorite is a secondary mineral and is formed by the alteration and decay of other minerals containing iron, magnesia and alumina, such as hornblende, pyroxene, and mica, in previously existent rocks. The dark green color of many igneous rocks is due to its formation in them; thus the dull green appearance, and more or less soft, earthy character of many traps and basalts is largely produced by the change of some of the original minerals into this substance. It is also of common occurrence in the metamorphic rocks; which, as in green slates, owe their

color to finely disseminated particles of it; while in chlorite-schist it is a prominent ingredient.

Clay, Kaolin. — Under the heading of clay several different substances are included, compounds of silica, alumina, and water. The most important of these is *Kaolin* which may be taken as the basis of true clay. Its chemical formula is $H_4Al_2Si_2O_9 = Al_2O_3 \cdot 2\,SiO_2 \cdot 2\,H_2O$. It consists of excessively minute thin platy or scaly crystals aggregated in masses. Soft; when wet coherent, forming a plastic mass, which dries coherent. Naturally white in color, but often tinted red or yellow by iron oxides, or gray to black by organic matter. On rubbing between the fingers kaolin has a smooth, greasy feel; a dry piece usually adheres to the tongue; when dry and breathed upon it has a peculiar odor, and this helps to detect its presence. Chiefly formed by the decay of feldspar. An important constituent of various rocks and soils.

Dolomite. — This word is used in two ways: mineralogically, as the name of a mineral, and geologically, as the name of a rock, largely or wholly composed of it. The mineral dolomite is a compound of one molecule of carbonate of lime with one molecule of carbonate of magnesia $CaCO_3 \cdot MgCO_3$. Its general physical properties of crystallization, color, hardness, etc., are so like those of calcite (page 439) that it is not easily distinguished from it. The best test is by chemical means; calcite effervesces freely in any weak acid when *cold;* to produce this with dolomite the acid must be *hot.* A further chemical test for magnesia in the solution after eliminating the lime is confirmatory. Many limestones and marbles are in part composed of dolomite, and may pass into dolomite in the geological sense. The origin of dolomite has been discussed on page 192.

Epidote. — This mineral is a complex silicate, containing variable amounts of alumina, iron and lime with some hydrogen. It may be considered a mixture, in varying proportions, of $Ca_2(AlOH)Al_2(SiO_4)_3$ and $Ca_2(FeOH)Fe_2(SiO_4)_3$. It often occurs in prismatic or bladed crystals with one perfect cleavage, or in grains, sometimes aggregated into masses. The color is green, from light to dark, and usually of a yellowish-oily tone. Too hard to be scratched with a knife. Epidote is a product of alteration of other mineral substances and is produced in regional or contact metamorphism, especially when impure stratified rocks containing calcareous matter, sand, clay, limonite, etc., are subjected to such processes.

Feldspar. — These are, perhaps, the most important of all minerals from the geological standpoint since the bulk of the rocks forming the continental masses appears to be most largely composed of them. They are silicates of alumina with lime, soda, or potash and accord-

ingly as one of these three is present different kinds of feldspar are recognized and named, as follows:

(*a*) *Orthoclase*, $KAlSi_3O_8$, silicate of potash and alumina.
(*b*) *Albite*, $NaAlSi_3O_8$, silicate of soda and alumina.
(*c*) *Anorthite*, $CaAl_2Si_2O_8$, silicate of lime and alumina.

Pure varieties of feldspar, of the compositions indicated above, are mostly confined to crystals found in veins and druses in the rocks; they sometimes occur as component particles of the rocks themselves, but are rare; in most cases the rock grains are mixtures of either orthoclase and albite on the one hand, or of albite and anorthite on the other, and are then known as:

(*d*) *Alkalic feldspar*, $(KNa)AlSi_3O_8$, mixtures of *a* and *b*.
(*e*) *Plagioclase feldspar* $(NaAlSi_3O_8)_x + (CaAl_2Si_2O_8)_y$, mixtures of *b* and *c*.

In (*d*), alkalic feldspar, the potash compound is usually in considerable excess and it is apt to be referred to as orthoclase, although not pure. In the plagioclase group all transitions from pure albite at one end to anorthite at the other are known; one mixture in which the two are about equal is called *labradorite*.

In physical properties the different kinds of feldspar are much alike. The outward crystal form is not a matter of much impor-

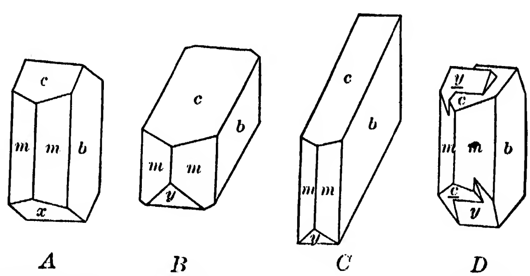


Fig. M_1.—Feldspar crystals of several types of development, *A*, *B*, *C*, *D*. In *D* a twin crystal (Carlsbad type) is seen.

tance, as it is rarely seen in rocks, except in the phenocrysts or large embedded crystals of porphyries (see page 327). In them the crystals usually have the shapes shown in *A*, *B*, *C*, and *D* of the adjoining Fig. M_1, and the outlines seen on a broken rock surface are various sections of these crystal forms. In Fig. M_1, *D*, two crystals are seen intergrown in what is known as a twin crystal; these may often also be observed in the rocks.

Feldspars possess two directions of excellent cleavage, one parallel to the face *b* of the crystals, the other parallel to *c*; these are at right angles to each other (orthoclase), or very nearly so (plagio-

clase). These cleavages give the broken surfaces of the grains seen in rocks minutely terraced or step-like appearances, whose levels in a single grain reflect light simultaneously. This is an important means of distinguishing feldspar particles from quartz grains in the rocks, the latter having no cleavage.

In color, the feldspars are usually white, pinkish to deep flesh-red, grayish, or yellowish, very rarely limpid and colorless, and of a porcelain-like appearance. Orthoclase is very often pink or red, plagioclase white, grayish, or yellow; this rule is by no means, however, an invariable one. A better means of distinguishing them, if it can be seen, especially by aid of a lens, is that one of the cleavage surfaces of plagioclases is often ruled by excessively fine parallel lines; this does not occur in orthoclase on account of its having a different crystallization from plagioclase. The feldspars are hard and cannot be scratched with a knife-point, but may be scratched with quartz; they are not acted upon by ordinary acids, properties which serve to distinguish them from some other cleavable rock minerals, such as calcite and dolomite.

Under ordinary processes of weathering the feldspars are chiefly changed into clay (kaolin); they may often be seen in the rocks more or less altered. They then become soft and yield the clay odor. In regional metamorphism, especially when combined with hydrothermal actions, they are converted into white mica, sericite, and take part in the formation of a variety of other secondary minerals.

Flint. — This is not a rock in the sense that it occurs in extensive independent formations, like limestone, nor is it a definite mineral, like calcite. It may, however, be considered conveniently here among the minerals. It is an intimate microscopic mixture of crystallized silica, SiO_2 (quartz), and non-crystalline silica containing some combined water (opal). Its color is dark gray, or black, from organic matter; its hardness is well known and like that of quartz; it cannot be scratched by the knife or by feldspar. It has no cleavage but a conchoidal fracture. Its use for striking fire and in furnishing the weapons and tools of primitive man are well known. Its occurrence in concretions and masses in chalks and limestones (in the latter often called *chert*) has been alluded to in this book (page **292**). Somewhat similar masses of silica, more or less pure, sometimes white or light gray, and often differently colored by iron (yellow, red, or brown) and other substances, in some cases of similar but often of different or uncertain origin, have been variously termed *jasper*, *jaspilite*, *hornstone*, *novaculite*, etc. In places, like the jaspilites of the Lake Superior region, or the novaculites of Arkansas, they may form beds of considerable importance.

Garnet. — This is the name of a group of minerals which have the common chemical formula $X_3Y_2(SiO_4)_3$, and are thus salts of orthosilicic acid, H_4SiO_4; X is either calcium, magnesium, or ferrous

iron, or mixtures of them (bivalent elements); Y is either aluminum, ferric iron, or chromium, or mixtures of them (trivalent elements). The pure compounds have received definite names, thus $Fe_3Al_2(SiO_4)_3$ is known as *almandite* and for the most part composes the *common garnet* ordinarily seen in rocks. Garnets crystallize in the forms shown in Fig. M_2, *A* and *B*, and crystals of these forms are often seen in the rocks, especially in the mica-schists. The type *A*, when poorly developed, often appears as a spherical object embedded in the rocks.

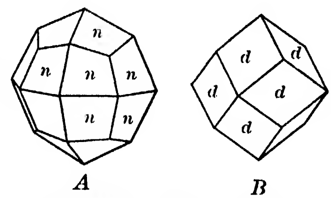


Fig. M_2. — Garnet crystals.

The mineral has no good cleavage, is very hard so that it cannot be scratched by a knife or by feldspar, and varies greatly in its colors; common garnet is deep red to brownish-red and sometimes black; yellow and brown tones are also common in garnets containing lime.

Garnets are found chiefly in metamorphic rocks; in gneisses and crystalline schists. Lime garnets $Ca_3Al_3(SiO_4)_3$ (*grossularite*) occur mostly in calcareous rocks, such as impure limestones which have been metamorphosed by the action of intruded igneous masses.

Gypsum. — This mineral, called also *selenite*, is the sulphate of lime with water, $CaSO_4 \cdot 2\,H_2O$. It is sometimes found in good crystals, of more or less tabular lozenge-shaped forms, but as a rock constituent it is massive, foliated with curved surfaces, or granular to compact, and less commonly fibrous. The crystals and large crystal grains have one perfect cleavage by which it may be split into thin sheets. The normal color is white or colorless, but it is often tinted reddish, yellowish, or even black by impurities. It is a soft mineral and may be readily scratched by the finger nail.

Gypsum rock is widely distributed in the stratified formations, in the form of extensive beds, often of great thickness and is especially found with limestones and shales. It is indicative of arid conditions prevailing at its time of formation. Its use in making plaster of Paris is well known; this is done by heating it until a portion of the water is driven from the molecule; on mixing with more water it is at first plastic, when the water has again been taken up it becomes hard.

Halite, see Rock-salt.

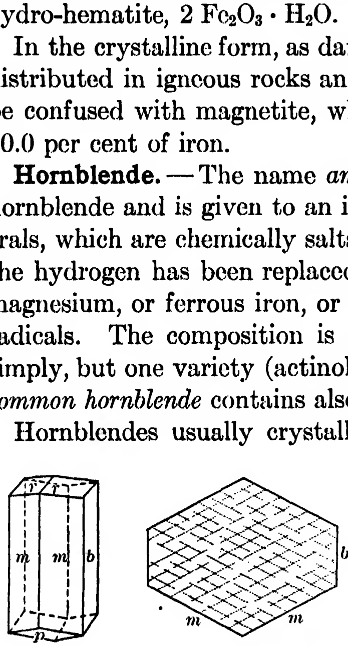
Hematite. — Red oxide of iron or ferric oxide, Fe_2O_3. This substance is found in several forms, one of which is crystalline with a steel-like luster, but the most important one geologically is known as common red hematite. In this condition it is not crystallized,

but is massive, granular to compact, often in rounded forms, sometimes earthy. It has no metallic luster, is opaque and of a dark red to brown color; its powder and streak are red (distinction from limonite). It occurs in sedimentary and metamorphic rocks in beds and masses, sometimes of great size, and furnishes a valuable ore of iron. It is also common as a cement of the grains of some stratified rocks, such as red sandstones, and as a coloring matter it is widely distributed in all kinds of rocks and soils, in some cases perhaps as hydro-hematite, $2\ Fe_2O_3 \cdot H_2O$.

In the crystalline form, as dark metallic looking specks, it is widely distributed in igneous rocks and certain crystalline schists, but may be confused with magnetite, which see. The pure mineral contains 70.0 per cent of iron.

Hornblende. — The name *amphibole* is used interchangeably with hornblende and is given to an important group of rock-forming minerals, which are chemically salts of metasilicic acid, H_3SiO_3, in which the hydrogen has been replaced by various metals, such as calcium, magnesium, or ferrous iron, or by mixtures of them, and by various radicals. The composition is too complex to be represented very simply, but one variety (actinolite) is very nearly $Ca(MgFe)_3(SiO_3)_4$; *common hornblende* contains also alumina and ferric iron.

Hornblendes usually crystallize in prismatic forms; the crystals are apt to be long and bladed, sometimes, as in some hornblende-schists, they may be very fine and needle-like; in some cases, as in certain porphyries, the prisms may be short and stout, Fig. M_3, A, or again the mineral may occur in irregular grains and masses, as in many diorites. In the igneous rocks the color is usually black to greenish-black; in the metamorphic rocks various shades of green to black, less commonly pale, or even whitish.



A B

Fig. M_3. — A, Hornblende crystal; B, section of crystal at right angles to vertical axis of prism showing angles of prismatic cleavage.

Hornblende is rather hard but all varieties may be scratched with quartz, some by a knife point. It has a highly perfect cleavage parallel to the prism faces, and the two directions of cleavage along the prisms meet at angles of 125° and 55°, Fig. M_3, B, a fact of importance in helping to distinguish it from pyroxene (see pyroxene). The glittering prismatic faces seen on the blades and needles of the mineral on a fractured rock surface are mostly due to this cleavage. In small grains it is difficult to distinguish from pyroxene.

Hornblende under proper conditions may be changed into serpentine, chlorite, carbonates, etc., and by continued weathering into limonite, carbonates, and quartz.

The hornblendes are important geological minerals and occur in a great variety of igneous and metamorphic rocks. They may be present in only a few scattered crystals, or to such an extent that the rock, as in hornblende-schist, is mainly composed of them.

Iron Ores. — These are chiefly *hematite, magnetite, limonite,* and *siderite* and information concerning them will be found under these headings.

Kaolin. — This is the basis of clay; see under *clay.*

Labradorite, a feldspar consisting of about equal mixtures of albite (soda-feldspar) and anorthite (lime-feldspar). Named from the coast of Labrador where it occurs in large crystals, often showing a play of colors. See Feldspar.

Limonite. — Yellow oxide of iron, $2\,Fe_2O_3 \cdot 3\,H_2O$, partly hydrated ferric oxide. Does not crystallize, but is found in earthy formless masses, which are sometimes compact and of rounded shapes, or stalactite-like, and may exhibit a radiating structure. There is no cleavage and the mineral, while usually dull or earthy in appearance, may in the compact globular forms show a silky, or even somewhat metallic luster. Color is usually brown, from light to dark, or brownish-yellow. The powder, or streak, is yellow-brown, which serves to distinguish it from hematite. Per cent of iron 59.8.

Limonite is found in several ways, but is always a secondary mineral, that is, one formed at the expense of previously existent ones by weathering and other agencies which act chemically upon them. In altered igneous and metamorphic rocks it may be seen as small earthy masses resulting from the decay of some previous iron-bearing mineral. It occurs in the sedimentary strata, see page 422, as masses and beds in compact, globular, or concretionary forms. As bog-iron ore it is loose, porous, and earthy. Finally, it forms the yellow coloring matter of many soils, clays, and sedimentary rocks. It is a valuable ore of iron.

Magnetite. — Ferrous-ferric oxide, $FeO \cdot Fe_2O_3$, (Fe_3O_4). Crystallizes in octahedrons, sometimes in dodecahedrons like Fig. M_2, B, page 443, but is usually seen in small grains in the rocks whose forms are irregular; sometimes in larger masses. Has no cleavage, is brittle and usually too hard to be scratched by a knife. Has a metallic luster, sometimes dull; is opaque and resembles bits of iron or steel in the rocks. Its property of being attracted by a magnet helps to distinguish it from other somewhat similar looking minerals.

Its powder or streak is black. Is widely distributed in igneous and some metamorphic rocks, usually in small grains but sometimes in larger masses, especially in contact metamorphic rocks, and is then a valuable ore of iron. Per cent of iron, 72.4.

Micas. — The micas are a group of rock minerals which are characterized by a remarkably perfect cleavage in one direction, by means of which they may be split into almost indefinitely thin, flexible, elastic leaves. They are silicates of complex composition and for practical purposes may be divided into two groups, *light* colored micas, of which *muscovite* may be taken as an example, and *dark* micas, or *biotite*, and related kinds. Muscovite, beside the silica, contains alumina, potash, and hydrogen; biotite contains in addition magnesia and iron. Their simpler formulas may be shown chemically as follows:

$$\text{Muscovite} = H_2KAl_3(SiO_4)_3.$$
$$\text{Biotite} = (HK)_2(MgFe)_2(AlFe)_2(SiO_4)_3.$$

They crystallize in six-sided (sometimes four-sided) tables, whose faces are nearly always rough, while the flat bases are formed by the glittering cleavage surfaces, Fig. M_4. They are also often seen in rocks in flakes, scales, or shreds, sometimes curled or bent, with shining cleavage faces. *Muscovite* is colorless to white, pale brown, or greenish; thin leaves are transparent. The huge crystals of it found in granite-pegmatite veins furnish the mica which is ordinarily used commercially. In very minute scales in the rocks it has a silky appearance and is known as *sericite*. *Biotite* is black and only translucent in thin scales. All micas are easily scratched with a knife; they are readily distinguished from chlorite and talc by the elasticity of the cleavage plates, and this and the cleavage distinguishes them from other rock minerals.

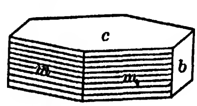


Fig. M_4. — Crystal of mica, showing cleavage parallel to base, c.

Biotite is found chiefly in igneous rocks, especially in granites, syenites, some diorites, in certain felsite lavas and porphyries, and in some trap-like rocks occurring in dikes. Muscovite occurs in pegmatite veins, but is especially found in the metamorphic rocks, as in gneisses, and is common in many crystalline schists; thus in mica-schist it plays the chief rôle. Under certain conditions, by the action of heated vapors and water, feldspars are converted into muscovite, especially the sericite variety.

Muscovite, see micas, above.

Ocher. — This name is given to clays colored deeply red or yellow by oxides of iron (hematite or limonite); thus red ocher, yellow ocher.

Olivine. — Silicate of magnesia, Mg_2SiO_4, the magnesia more or less replaced by ferrous iron. Crystals are rarely well developed in rocks; commonly it appears in grains or small granular masses. Color olive to yellow-green; bottle-green very common; transparent to translucent, often turns reddish and opaque by oxidation of the iron. Hard, cannot be scratched with knife-point; glassy luster.

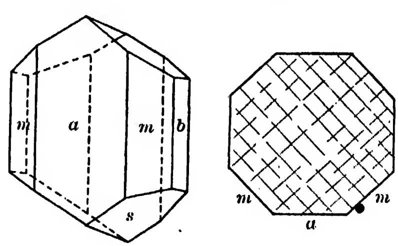
Olivine, often called chrysolite, occurs almost entirely in ferro-magnesian igneous rocks, as in gabbros, peridotites, dolerites and basalts. It is often seen in the basalts scattered in small bottle-green grains. A variety of peridotite composed of almost pure olivine occurs in several regions and is known as *dunite*. The mineral alters readily to serpentine and is probably the chief source of this substance.

Orthoclase. — See Feldspar.

Plagioclase. — See Feldspar.

Pyroxene. — This is an important group of minerals which, like the hornblendes, are salts of metasilicic acid, H_2SiO_3, in which the hydrogen has been replaced by magnesium, calcium, and iron, or by mixtures of them, and in some cases by sodium, or various radicals. As ordinarily seen in the rocks the light-colored pyroxenes are mostly *diopside*, $CaMg(SiO_3)_2$, with little or no iron, while the dark or black kinds, commonly seen in igneous rocks, are apt to be the variety known as *augite*. Other varieties, such as *hypersthene* $(MgFe)SiO_3$, also occur, but are of less importance.

All pyroxenes have the common property that they form prismatic crystals with a double cleavage parallel to the main prism faces, which intersect at nearly right angles (93° and 87°). The crystals are apt to be short and stout, and well-formed examples of augite are often found in basaltic porphyries and lavas, see Fig. M_5, *A* and *B*. Pyroxenes are also found in grains and more or less shapeless masses, as is common in gabbros and dolerites.



A *B*

Fig. M_5. — *A*, augite crystal. *B*, section normal to vertical axis, showing prismatic cleavage.

Pyroxenes, while sometimes white, or even colorless (pure diopside), are usually colored more or less greenish, light to dark, while augite is black and opaque. Some can be just scratched by a knife-

point, all are scratched by quartz. The luster, which is often wanting, is glassy.

Pyroxenes resemble hornblendes in the rocks and are frequently difficult or even impossible to distinguish from them. The slender-bladed forms, and excellent glittering cleavage of hornblende often aid in discriminating it from pyroxene whose cleavage is not so good, and whose crystals are apt to be shorter and stouter. A comparison of the angle at which the cleavages meet (pyroxene 93°, 87° and hornblende 55°, 125°, compare Figs. M_3 and M_5) also helps to distinguish them. But it is often impossible, as in dolerites, to discriminate between them by simple observation and without other methods of testing. Pyroxenes are very important minerals in the igneous rocks, especially in the dark-colored ferromagnesian kinds, such as gabbros, dolerites, and basalts, which are largely composed of the augite variety. In the feldspathic rocks, such as syenite and certain felsite lavas, they sometimes occur, but are of less importance. While they are found in some metamorphic rocks they are of far less importance in this class than the hornblendes. Indeed by metamorphic action pyroxene is generally converted into hornblende, and much of the latter in the schists owes its origin to such conversion of pyroxene, when previous igneous rocks have been changed into them.

Quartz, pure silica, SiO_2. Crystallizes in hexagonal prisms capped by a six-sided pyramid. This is the common form in veins, druses, geodes, and other cavities in rocks, Fig. M_6,*A*. In embedded phenocrysts in porphyries the prism is apt to be small or wanting, see Fig. M_6,*B*, the form is poorly developed and the crystal has usually a roughly spherical shape. In general it has no outward crystal form but, as in igneous rocks such as granite, it is in small shapeless masses. In quartz veins it may be massive; in sandstones it is in cemented rounded grains, and these in quartzites may be so firmly cemented as to form practically massive quartz.

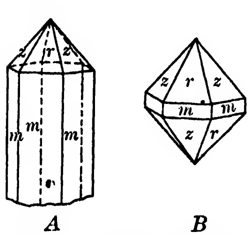


Fig. M_6. — Quartz crystals.

Quartz has no cleavage, but a conchoidal fracture which helps to distinguish it from feldspar in many rocks. In color the well-formed crystals of veins are usually colorless, or smoky-brown, sometimes purple, but the rock-making quartz is generally white, smoky, to brown, rarely black; massive quartz of veins is usually white. The luster is glassy to greasy; the mineral is hard and cannot be scratched by a knife but scratches glass and feldspar.

It is one of the commonest of minerals and occurs in igneous, sedimentary, and metamorphic rocks. With feldspar it composes more or less entirely the bulk of granites, many felsites, and is found in some diorites. Occurs also in gneisses and many schists. In pure sandstones and quartzites it may be almost the only mineral present. Excepting limestones, chalks, and marbles, and the dark heavy igneous rocks, like dolerite and basalt, its presence in rocks should, at least, be always suspected. It is not acted upon by the ordinary agents which decompose other rock minerals and this accounts in part for its wide distribution, and also its being so commonly one of the constituents of soils.

Rock-salt, halite, sodium chloride, $NaCl$. Easily recognized by its cubic crystals, good cubic cleavage, ready solubility and saline taste. Colorless and transparent to white, translucent, sometimes tinted. Common salt is the only chloride in nature which is of wide geological importance. In addition to its occurrence in the sea it forms beds, sometimes enormously thick, in the sedimentary formations, usually in clays and shales, and is generally accompanied by gypsum. Its presence is thus indicative of arid conditions at the time of its deposition.

Serpentine. — Hydrated silicate of magnesia, $H_4Mg_3Si_2O_9$ ($2\,H_2O \cdot 3\,MgO \cdot 2\,SiO_2$). This mineral does not crystallize but is generally found massive, sometimes granular and not infrequently fibrous, with fine, silky, flexible, and easily separated fibers. The color is usually green from light to dark and more or less yellowish or olive in tone; sometimes nearly black. Fibrous varieties white to brown, often pale brownish. Luster greasy, wax-like; has a greasy feel; soft, readily scratched or cut by a knife; translucent to opaque.

Serpentine is a secondary mineral resulting from the alteration of previously existent magnesia-bearing silicates, such as hornblende, pyroxene, and especially olivine. It appears to be formed by the action of heated waters on igneous and metamorphic rocks and is found as masses and layers, sometimes associated with igneous, often with other metamorphic rocks. The fibrous variety, called also *chrysotile*, usually occurs in seams, in massive serpentine. Greenish and yellowish serpentines are frequently cut and used as ornamental stones in decoration and building.

Siderite; ferrous carbonate, $FeCO_3$. Carbonate of iron, when a pure mineral, is extremely like calcite and dolomite, whose properties should be consulted. It crystallizes in a similar form, has the same rhombohedral cleavage, and like them is soft and attacked by acids with effervescence; apt to be brownish in color. The crystallized mineral is not of great geological or economic importance, but massive siderite, either compact or granular in character, is a valuable iron ore. Beds of it, more or less impure with admixed clay and limonite, have

a wide distribution and are known as *clay-iron-stone*. A variety colored black by coaly matter is known as *black-band* ore. In many places these deposits are of great technical value. Per cent of iron in the pure mineral, 48.21.

Talc. — This mineral, like serpentine, is a secondary silicate of magnesia, $H_2Mg_3(SiO_3)_4 = H_2O \cdot 3\,MgO \cdot 4\,SiO_2$, produced by the action of circulating heated fluids on previously existent silicates, such as hornblendes, pyroxenes, and olivine. What the conditions are which determine its formation, rather than that of serpentine, are not known. The two are sometimes found associated.

It is usually seen in compact or strongly foliated masses, sometimes in scaly aggregates. Has a perfect cleavage in one direction like mica, but the cleavage leaves, though flexible, are not elastic. Has a mother-of-pearl luster and a soft greasy feel. Softer than chlorite, marks dark cloth with a white streak. Color white to greenish or gray; usually translucent.

Talc is only important in the metamorphic rocks where it occurs in talc schist and in the more massive rock known as *steatite* or *soapstone;* in the latter it is usually more or less mixed with chlorite.

Minerals Important as Ores

Introductory. — There are certain minerals which are not of importance in a broad geological sense, because they occur in such small amounts in the earth's crust, but are yet of great importance to man on account of the fact that they are the chief sources of supply for the metals used in commerce and the arts. Gold is a good example of this, its value as a medium of exchange depending for the most part on its rarity.

The ores of iron stand in an intermediate position, for they are not only important technically, but also as rock-minerals, as previously shown. The metals which are of most importance and whose chief ores are described are *gold, silver, lead, copper,* and *iron.*

Gold

This metal occurs in nature chiefly in the native state, as metallic gold. Its properties are too well known to need further mention, but it may be added that it is easily distinguished from other substances that may resemble it in color, such as iron-pyrites, by its softness and malleability, as it is rather easily cut by the knife and may be hammered out into thin plates.

Silver

This metal occurs as native metallic silver and combined with sulphur and also arsenic in several minerals. An occurrence, imperceptible to the eye, but of great importance, is that lead and sometimes copper ores are frequently enriched by its presence; it is extracted during the process of metallurgical treatment to which they are subjected to obtain the metals.

Native Silver. — Is distinguished by its color, softness and malleability, in which it resembles gold.

Argentite, Ag_2S, silver sulphide, is perhaps the most common form in which silver occurs in combination. It is usually massive, sometimes in crystal groups, has a shining metallic luster on a fresh surface but commonly appears black and dull. It can be easily cut, like lead, with a knife and is very heavy. On fusing it the sulphur burns off leaving pure silver behind. Percentage of silver 87.1.

Lead

Galena, PbS, lead sulphide, is one of the most common ores of lead. In color it resembles lead, but is brittle and breaks with a perfect cubic cleavage. It is usually crystallized in cubic forms or is in cleavable masses. It is very heavy and easily fusible. Percentage of lead 86.6.

Cerussite, $PbCO_3$, lead carbonate. Occurs in white or colorless crystals, or in granular whitish crystalline masses. Crystals have a very high luster. It is very heavy for a non-metallic appearing mineral. It is easily fusible, yielding lead and lead-oxide; dissolves in warm dilute nitric acid with effervescence, and a little sulphuric acid produces a precipitate of white lead sulphate in the solution. Percentage of lead 77.5.

Anglesite, $PbSO_4$, lead sulphate. Generally in whitish masses, granular to compact, but also occurs in white to colorless crystals. The massive varieties are dull to earthy in appearance, but the crystals have a high luster and are cleavable. Like cerussite unusually heavy, but easily distinguished from it by the lack of effervescence when treated with nitric acid. Fuses easily. Is often found associated with galena, as an alteration product of it. Percentage of lead 68.2.

Copper

Native copper, the metal sometimes occurs as an ore, especially in the Lake Superior region; its properties need no further description.

Cuprite, Cu_2O, copper oxide, or ruby copper as it is often called, usually occurs in massive form but sometimes in crystals showing the form of the cube or octahedron. It has a high luster in the crystals to sub-metallic or dull when massive. The color is red and in clear crystals ruby-like. Easily fusible, tingeing the blowpipe flame green; is also very heavy. Percentage of copper 88.8.

Chalcopyrite, $CuFeS_2$, copper pyrites. This is one of the most important ores of copper. It commonly occurs in compact, massive form and has a brass yellow color and metallic appearance; it is often tarnished. It resembles common iron pyrites, FeS_2, but is easily distinguished from it by its softness as it can be easily scratched with a knife. Is moderately heavy. Percentage of copper 34.5.

Chalcocite, Cu_2S, copper glance. Generally found massive, crystals rare. Has a conchoidal fracture, a metallic luster, color of lead and shining on fresh surface but often tarnished and black; is heavy and has a black streak or powder. Fuses easily; dissolves in nitric acid and solution gives the blue color of copper with ammonia; is soft and easily scratched with a knife. Common in the secondary enrichment zones of veins containing copper. Percentage of copper 79.8.

Malachite, $Cu(OH)_2CO_3$, green carbonate of copper. Occurs in crusts or rounded masses, often with a velvety surface, of a bright green color of varying shades, and with a fibrous, radiating structure. Usually dull in luster and opaque. Soft, easily scratched with a knife. Dissolves in acid with effervescence. Percentage of copper 57.4.

Azurite, $2\,CuCO_3 \cdot Cu(OH)_2$, blue carbonate of copper. Often in distinctly grouped crystals, also in rounded radiating masses. Of a deep azure blue color. Crystals with glassy luster and often transparent; soft, easily scratched with a knife. Like malachite dissolves in acid with effervescence. Percentage of copper 55.3.

Iron

The ores of iron, hematite, limonite, magnetite and siderite have been already described under the preceding group of rock-minerals. A remaining iron mineral of importance is pyrite.

Pyrite, FeS_2, iron pyrites. Commonly seen in crystals, of a cubic, or related form; crystals often striated on the faces; also occurs massive. Of a brass yellow color, sometimes tarnished; of a high metallic luster and opaque. Very hard, cannot be scratched with a knife, which distinguishes it from chalcopyrite. Its hardness and brittleness distinguish it from gold, for which it is sometimes mistaken. It is not used as an ore of iron, but is sometimes mined for sulphur.

Gangue Minerals

Common gangue minerals associated with ores are *quartz, calcite, dolomite, siderite* and *pyrite,* previously described in this appendix. In addition two other rather common gangue minerals may be mentioned, *barite* and *fluorite.*

Barite, $BaSO_4$, barium sulphate, commonly called "heavy spar." Generally in divergent groups of tabular crystals, also massive, coarsely cleavable or granular. Has perfect cleavages. Generally light colored, whitish, bluish, or reddish brown, crystals sometimes transparent; luster glassy or pearly. Heavy for a non-metallic mineral. Insoluble in acids and does not effervesce. Characterized by its good cleavage, light color and heaviness.

Fluorite, CaF_2, fluoride of calcium; fluor-spar. Usually in cubic crystals, but also massive and coarse to fine granular. Color generally light green or purple, rarely white, bluish, etc., commonly transparent to translucent and of glassy luster. Has a perfect cleavage in four directions by which it may be cleaved into octahedrons. Easily scratched with a knife; not a heavy mineral like barite. Does not effervesce with acids, which distinguishes it from carbonates (calcite, etc.).

INDEX TO PART ONE

Asterisks refer to illustrations